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IRON ORE AT BOMI HILL, LIBERIA.

E. F. FITZHUGH, JR.

ABSTRACT.

The iron deposit at Bomi Hill holds as much interest on geologic grounds as the exceptional high quality of its ore arouses among furnace men. The deposit has features in common with both the Venezuelan ores and those of the Adirondacks. The Liberian iron formation is composed of thinly laminated, alternating layers of quartz and crystalline hematite with minor magnetite. At the base of the formation there is massive ore that resembles some of the ores in the Grenville series of New York. The bulk of the known tonnage is in a doubly plunging synclinal structure. The surface manifestations are well delineated, showing induration and recrystallization of ore, comparative resistance of ore and nearby canga to erosion, and slow weathering of the outcrop and float ore through solution. The areal distribution of canga capping sheds pertinent light on the origin of this typical tropical teaser.

THE initial exploration of Bomi Hill was a modest diamond drilling program by Dutch interests in the late 1930's. In 1944 W. H. Newhouse, T. P. Thayer, and A. P. Butler, Jr., mapped and studied the deposits in a survey under joint sponsorship of the Liberian Government and the U. S. Geological Survey. The basic data developed in their investigations have been the foundation for subsequent activities.

While in Africa on wartime military duties, Lansdell K. Christie learned of Bomi Hill. After the close of hostilities, Mr. Christie's well founded faith in the area led him to seek exploration and mining rights from the Government of Liberia. He then organized the Liberia Mining Company, of which he is President, to develop and operate the mine. At this time the deposits could be reached only by 40 miles of jungle trail stretching northward from the equatorial Atlantic port of Monrovia. Despite the difficulties of a tropical environment and the distance to a steel plant, the Liberia Mining Company from its inception made steady progress toward production. The pace increased early in 1949 when Mr. Christie established a market for much of the planned output and arranged for financial and technical participation with Republic Steel Corporation.

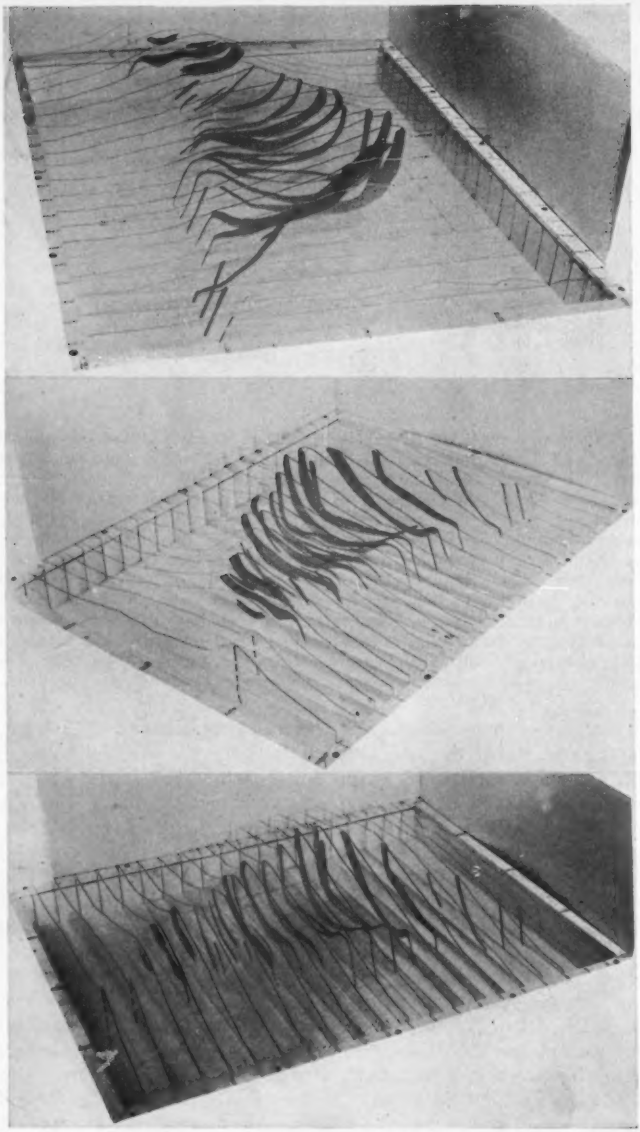


FIG. 1. Model of Ore Zone. a. looking southeasterly; b. looking southwesterly; c. looking more southerly than in view b.

In the succeeding two years loading facilities at the Monrovia dock were installed, a railroad now connects mine and port, a crushing plant was erected, and other mine preparations advanced. The first shipment of ore came into Baltimore in June, 1951, and in the following months production mounted to the planned rate of 1,000,000 tons a year.

The shape of the ore zone is shown by the series of vertical cross sections that made up the model, Figure 1. The steep dipping, thinner mineralization that marks the northern limit of the ore zone is conformable with through-going strata of iron formation that extend well to the east and west of Bomi Hill. The general relationship of ore to surrounding rocks is shown in the cross section, Figure 2. Resting on a gneissic granite footwall, a portion of the ore is immediately overlaid by a partially chloritized amphibolite gneiss.

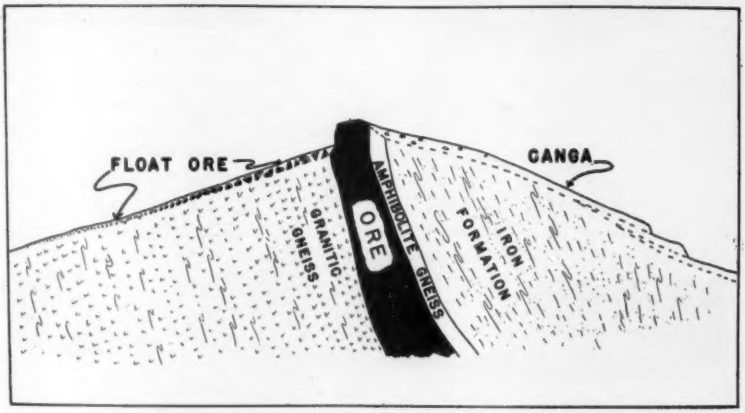


FIG. 2. Schematic cross section looking westward.

Elsewhere, iron formation, which is the main hanging wall rock, is in direct contact with the ore.

Rock deformation and metamorphism have been fairly strong in the region. Alteration minerals are common near the ore. The texture of the primary ore, its high magnetite content and the granitic gneiss nearby are all similar to the associations found in the New Jersey-Adirondack-Ontario iron belt. The quartz-banded iron formation and the surface expressions resemble the Venezuelan deposits. The intensity of metamorphism and of conditions surrounding deposition at Bomi Hill appear to have been somewhere between these two types. Such evidence on the ore deposition as is now available suggests that the massive Liberian ore bodies were formed by hydrothermal processes perhaps near the close of the granitic invasion.

The ore is dense and massive, and is roughly two-thirds magnetite and one-third hematite. In outcrops, a part of it consists of tightly interlocked crystal grains measuring up to ¼ inch on a side, and part is quite fine grained

with a steely appearance on freshly broken faces. Drill cores from depths of 100 or more meters show none of the steely ore, and, with depth, the interlocking and adhesion between mineral grains is generally less pronounced. Assaying over 68% Fe and low in P and S, Bomi Hills lump ore is an outstanding ore for the open hearth (Fig. 3).

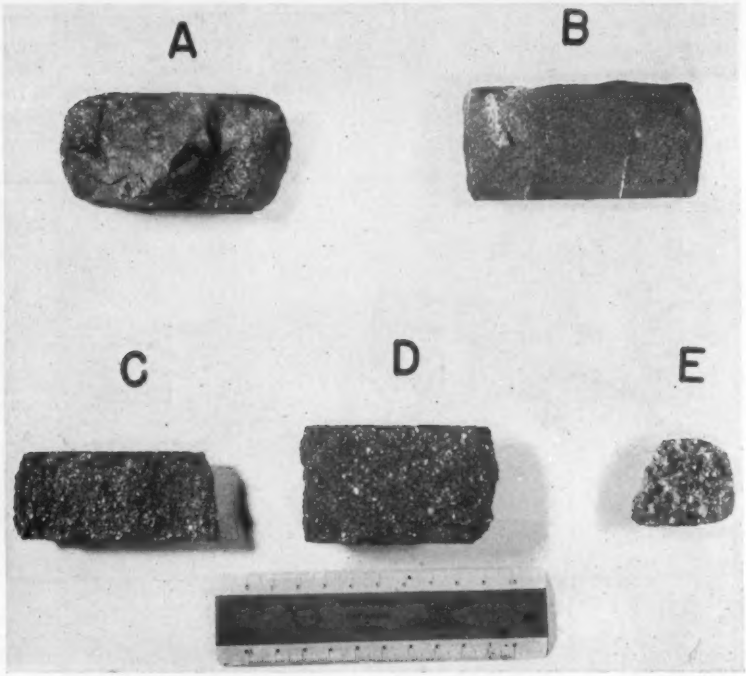


FIG. 3. Varieties of ore. a. 2 mm veinlet of steely ore in coarser matrix; b., c., d., e., show progressively coarser grain sizes.

The Bomi ore is an unusually pure ore of a type normally attributed to replacement by solutions of igneous or near-igneous characteristics. Yet adjacent to this ore there is a thicker, lower grade zone of iron formation. This thin-bedded, siliceous iron formation almost certainly had its origin in cyclical marine precipitation. As more is learned about the relationships between the sedimentary formation and the quasi-igneous ore, data may emerge that will be pertinent to comparable areas where either the sedimentary or the igneous aspects are less obvious.

Turning from the primary deposition, which is today a promising field for further study, the more superficial mineralization at Bomi Hill is also intriguing (Fig. 2). By a happy combination of structure, lithology, and re-

sultant topography, massive ore forms the crest of a curved, elongated hill. Opposite slopes of this hill show marked contrasts. The southern and western slopes have the footwall granitic gneisses for bedrock, whereas iron formation and incidental iron-rich silicate rocks underlie the slopes on the hanging wall side of the ore. The contrast between the float ore mantle on the footwall slopes, and the canga capping on the hanging side is fully as sharp as the difference of underlying rock types. Indeed, the divergent surface showings may well be closely related to their corresponding bedrocks.

Induration (with varying amounts of recrystallization) would seem to be the normal rather than the exception for high-grade iron-ore outcrops in the tropics. Paralleling Bomi Hill, Cerro Bolivar ore, which at depth is a crystalline hematite sand, has been hardened in a substantial capping and also in zones where downward circulating surface waters appear to have been channeled. Again at El Pao, the outcrops of dense, coarse, crystalline ore on Gutierrez Hill show even harder, weather resisting, fine-grained, steely streaks identical in appearance with the steely African ore. The cross-cutting pattern of these streaks and their near surface occurrence both at El Pao and at Bomi Hill suggest that the recrystallization is best attributed to meteoric waters penetrating and percolating along fractures. The recrystallization just has not progressed as far at El Pao as in zones at Bomi Hill.

The float at Bomi also shows the induration and relative lasting qualities of the ore. The mantle of float ore on the footwall slopes rests on and partly in kaolinic clay weathered from the underlying gneiss. Near the outcrop the float is coarse and angular with some exceptional blocks weighing many thousand tons. From an average size of perhaps 500 pounds adjacent to the outcrop, the float becomes progressively smaller and more rounded until pea-size spherules are typical of the base of the hill. The gentle slopes, where float has moved only by slow creep, show the more perfect gradations. The rounding and reduction in size have all the characteristics of solution by surface waters. Furthermore, while coarsely crystalline ore float is common near the outcrop, the rounded fragments on the lower slopes, to which surface waters have had longer access, are predominantly fine-grained. It is noteworthy that, both in veinlets as that is Figure 3(A), and in the steely float, the fine-grained ore has practically the same proportions of hematite and magnetite as the coarser grained ore from which it presumably formed.

A parallel gradation of rounding and size of ore float may be clearly seen on a slope at the San Isidro deposit in Venezuela.

On the hanging wall side of the Bomi Hill ore the siliceous iron formation is capped in large part by canga. The capping may range up to 30 feet thick. Near the ore outcrop, scattered fragments of ore are cemented in the canga mass. The cementing material is a porous, hard limonite with irregularly rounded cavities typically ¼ inch across. The walls between cavities are, in places, roughly banded and consist essentially of one or more hard, brown, limonite minerals. Wall thicknesses normally range from ¼ to ½ inch. Some cavities contain yellow to brown limonite powder, some have loose, granular quartz, and others are void.

The contained ore float boulders decrease and are finally lacking as the canga is followed away from the ore outcrop. Toward its down slope limits, the canga is terraced with faces 3 to 10 feet high. Such terraces, quite similar in contour to the terraces found around hot springs, are also common in the Venezuelan iron belt.

The chemical composition of the canga is variable. Its overall average grade may be about 50 percent iron with silica between 5 and 10 percent.

There is every indication that the porous, hard limonite of canga cappings is deposited by waters of meteoric origin. There is a strong suggestion that the iron itself has been previously dissolved largely if not entirely from siliceous, iron-rich rocks, rather than from high-grade iron ore. That canga can be derived from siliceous iron formation in the absence of high grade, massive, ore has been demonstrated recently on certain mountains in the Maria Luisa group in Venezuela. Again, if iron dissolved from massive ore were a sufficient source of canga, why is canga noticeably lacking on the footwall slopes of Bomi Hill? It is interesting to note that, although the distribution of canga and of siliceous iron formation is more complex at Cerro Bolivar than at the Liberian deposit, the localization of canga has led geologists there also to suspect that the limonitic capping may be derived only from the iron formation.[1]

On either side of the equatorial Atlantic the quartz-banded iron formations carry some 45 percent Fe and about 25 percent SiO_2. The five to ten percent silica in the limonite cangas is several times the silica content of the high-grade ores. Where blocks of iron formation are found cemented in the surface of the limonite cappings, differential leaching of the laminae that make up the blocks is common. Indurated hematite stands out in a multitude of tiny ridges, but the intervening silica layers have been leached to depths of ½ inch or more. Here is quartz being dissolved by meteoric waters. It is a more than adequate source of the redeposited silica in the nearby canga.

Continued attention to the canga questions is desirable. Many of these cappings are certainly derived from siliceous formations. Whether they may be attributed exclusively to such sources remains to the determined. Bomi Hill, with its happy combinations of topography and contrasting rock types, and the corresponding contrasts seen on the surface, sheds its share of light on the behavior of iron in the tropics.

As development and mining progress, more features of the near surface geology will become clear. Likewise, aspects of the primary ore deposition with more than local significance may well be disclosed.

REPUBLIC STEEL CORP.,
CLEVELAND, OHIO,
April 13, 1953.

[1] F. W. Wright, Jr.—Oral communication.

RECONNAISSANCE OF SUPERFICIAL PHOSPHATE DEPOSIT NEAR MINAS, URUGUAY.[1]

EDWIN B. ECKEL AND CHARLES MILTON.

ABSTRACT.

The phosphate deposit in Uruguay described here is of interest primarily because it is believed to be a superficial deposit that resulted from the action of guano on volcanic rock. Even though some of the rock contains as much as 30 per cent P_2O_5, it is unavailable as a source of fertilizer because the phosphate is combined with aluminum and iron as variscite and strengite, and possibly other equally insoluble minerals.

FIFTEEN km north of the town of Minas (which is about 100 km northeast of Montevideo on Highway 8) is a thick series of volcanic flows, resting on granite. The flows strike northeast and dip 10°–15° southeast at Gruta y Cerro Arrequita, the location of the main phosphate deposit (Fig. 1). This is a hill, some 1.5 km wide and two or three times as long. The northwest-facing edge is a steep scarp or cliff, more than 100 meters high, with much talus at the base (Fig. 2).

The hill itself is made up of a series of light-colored flow rocks, some of them agglomerates and welded tuffs, ranging in composition from rhyolitic to andesitic; most of them contain abundant phenocrysts or fragments of quartz as well as small phenocrysts of pink and white feldspars.

Several near-vertical fissures roughly parallel the cliff faces (Fig. 2). These may represent deep-seated faults, but more likely they are near-surface cracks or joints along which the rocks have slid downward in the development of the cliffs. Several of these fissures are a meter or more wide in places, and they extend downward several scores of meters. There is at least one extensive cave (which explains the word Gruta in the locality name) that is related to these fissures. It is actually a large irregular opening between tumbled blocks of rock rather than the more familiar kind of solution cavity of limestone regions. Only the entrance to this cave was examined.

Most of the phosphatic material has been found along the lower parts of the cliff and in the talus below it. The rocks exposed in the upper cliff faces are mostly fresh and unweathered. Some of the lower beds, however, are altered to a spongelike crumbly mass for depth of a few inches to several feet from the surface. Angular blocks of similar crumbly material are abundant in the talus slope. The rock material between the walls of the above-mentioned fissures is even more thoroughly leached and spongy than the weathered and altered rock on the cliff faces. The altered material is composed largely of the siliceous matter in the original rock, plus phosphatic material in varying amounts that has partly replaced other constituents.

[1] Publication authorized by the Director, U. S. Geological Survey.

DISTRIBUTION OF PHOSPHATE.

Petrologic examination of available specimens, taken in conjunction with the results of chemical analyses by the U. S. Department of Agriculture, proves conclusively that the highly phosphatic material is confined to weathered and otherwise altered rocks very close to the surface. Some of the samples with high phosphate content came from blocks of altered rock in the talus at the foot of the cliff.

FIG. 1. Index map showing location of phosphate deposit near Minas, Uruguay.

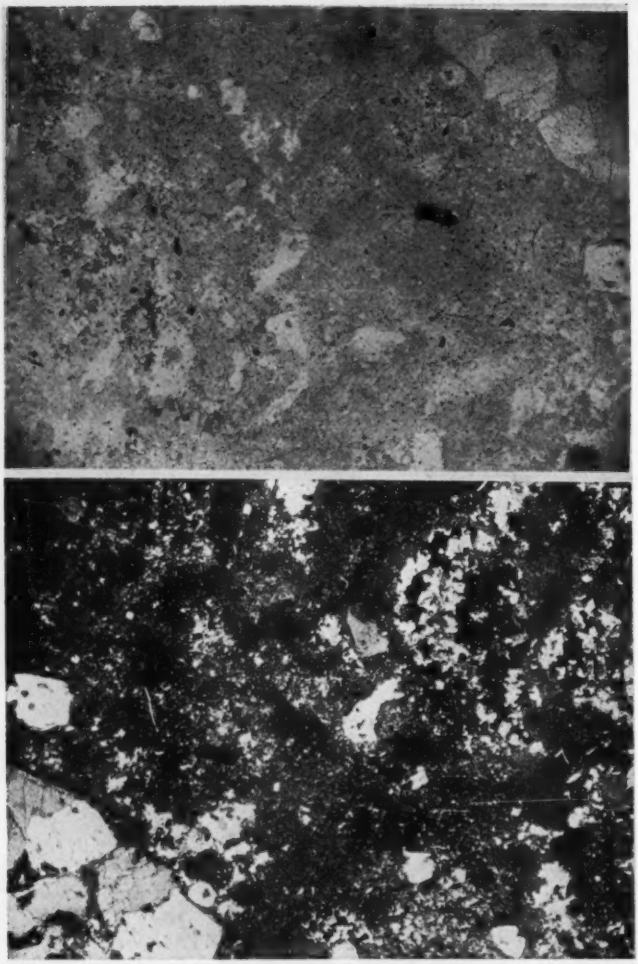
The fresh rocks are felsites with quartz phenocrysts and a few feldspar phenocrysts in a microcrystalline groundmass that is largely made up of a fine-grained intergrowth of quartz and feldspar. (Figs. 3a, 3b.) The apparently fresh and unphosphatized rocks contain less than 0.5 percent P_2O_5; part at least may be present as apatite, a normal minor constituent of igneous rocks.

In all the altered rocks the dense groundmass and even parts of some of the phenocrysts are partly replaced by irregular masses of phosphatic material. (Figs. 4a, 4b, 5a, and 5b.) In at least one specimen this material makes up nearly half of the rock mass.

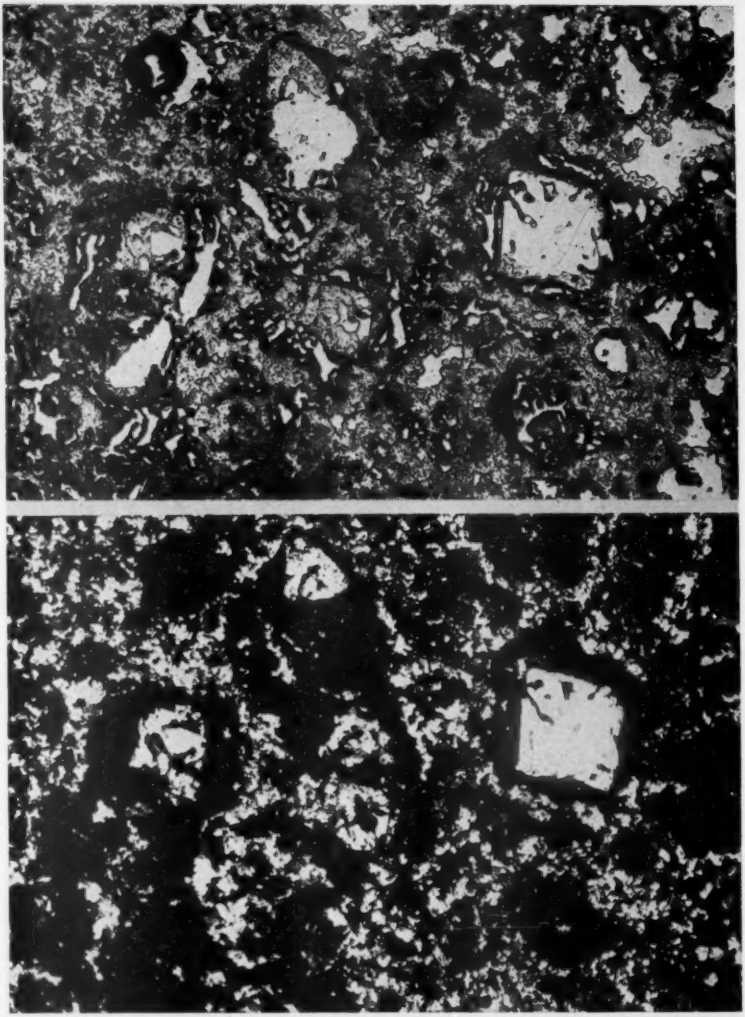
The phosphatic material is too fine-grained to permit ready mineral identification. Some of it is isotropic, and probably in part represents one or more of the complex alkali phosphates; and some of it may be submicroscopically crystallized "statistically isotropic" variscite-strengite. Spherulitic anisotropic aggregates make up most of the phosphatic material, however. Their optical characteristics are those of the iron-aluminum phosphate minerals such as variscite-strengite ($AlPO_4 \cdot 2H_2O$–$FePO_4 \cdot 2H_2O$). The conclusion

FIG. 2. Northwest face of Gruta y Cerro Arrequita. The volcanic rocks along the cliff face and along open fractures are partly phosphatized. Much of the talus at foot of cliffs is made up of phosphatized rocks.

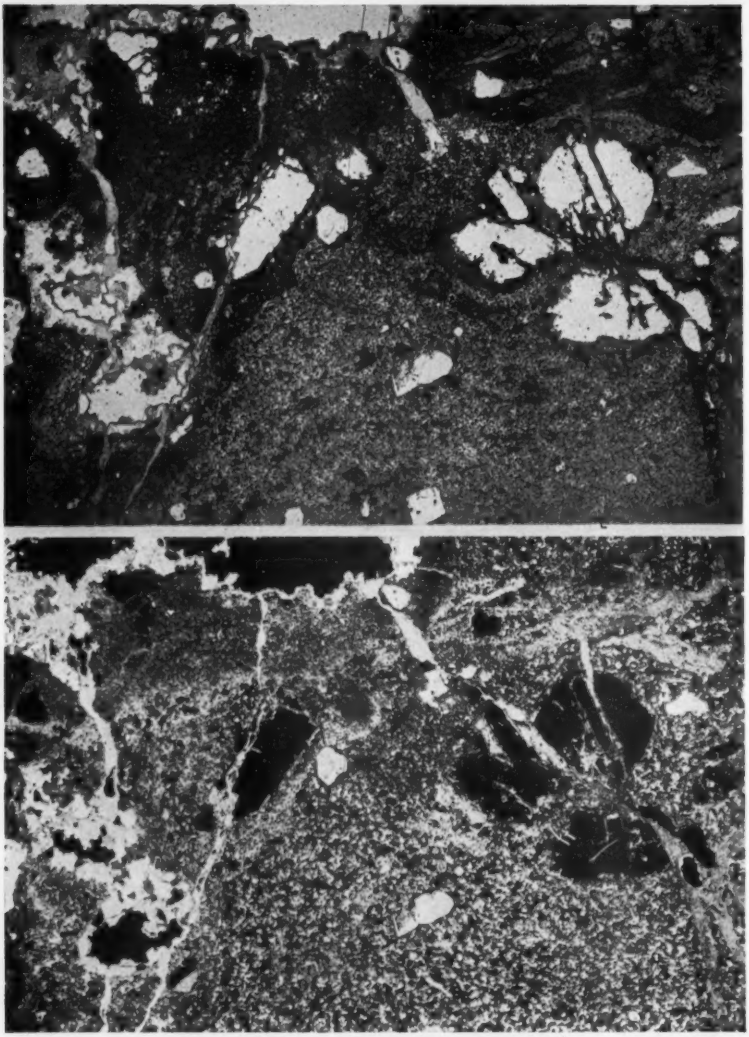
that most of the phosphate is in the form of variscite-strengite is supported by the chemical analyses below as well as by X-ray investigation (U. S. Geological Survey films 6397, 6398, 6399). The fact that all three X-ray films show small amounts of an unidentified substance in addition to variscite-strengite strongly suggests that some other complex alkali aluminum-iron phosphates are also present.



FIGS. 3a, 3b. Thin section, ordinary light and crossed nicols, × 15. Unphosphatized volcanic rock. The rock is weathered slightly, and not visibly if at all phospatized. The photomicrographs show a typical felsic texture, with coarse quartz phenocrysts in a fine grained feldspathic-quartz aggregate. The dark areas in the upper picture (ordinary light) are iron-oxide debris from formerly existing ferromagnesian silicate minerals.



FIGS. 4a, 4b. Thin section, ordinary light and crossed nicols, × 20. Strongly phosphatized volcanic rock. Shows groundmass of felsite porphyry largely replaced by isotropic aluminum phosphate (turbid under ordinary light, black under crossed nicols). Right of center is a crystal of quartz, with strong rhombohedral development, characteristic of porphyritic quartz in volcanic rocks, and also showing characteristic embayment or corrosion, with phosphate filling the embayments.



FIGS. 5a, 5b. Thin section, ordinary light and crossed nicols, × 15. Partly phosphatized volcanic rock. Quartz phenocrysts in a microcrystalline groundmass, characteristic of the felsitic rocks. Quartz is shattered and corroded, a feature common to phosphatized rocks, possibly related to the action of strong alkali solutions. The streaked areas are aggregates of strongly anisotropic spherulites of phosphate, probably variscite, $AlPO_4 \cdot 2H_2O$. The felsic groundmass likewise contains innumerable isolated spherulites.

A suite of five specimens were partially analyzed, as follows:

ANALYSES BY W. L. HILL, PRINCIPAL CHEMIST, U. S. DEPARTMENT OF AGRICULTURE.

	Al_2O_3	Fe_2O_3	P_2O_5
1. Wall of cave near gate	2.7	11.3	13.0
2. Loose material from ledge	—	—	10.3
3. Loose rocks from ledge	15.4	6.5	26.7
4. Large rock beyond gully	—	—	0.3
5. Large rock beyond gully	—	—	0.0

Speciments 4 and 5 are unphosphatized felsite porphyry; the others—1, 2, and 3—have been phosphatized. The $R_2O_3 : P_2O_5$ ratio is close to 1:1 in Nos. 1 and 3, corresponding to variscite-strengite.

Figures 4a and 4b show the microscopic structure of No. 3. (Another specimen of very similar material contained 30 percent P_2O_5.)

A second suite of specimens, reported by the discoverer of the deposit to be representative of a 600- to 700-acre area underlain by talus, gave the following partial analysis:

ANALYSES BY ROBERT M. MAGNESS, CHEMIST, U. S. DEPARTMENT OF AGRICULTURE.

	3005-a	3005-b	3005-c
P_2O_5	23.45	27.92	0.44
CaO	Trace	Trace	—
Fe_2O_3	4.16	8.50	—
Al_2O_3	considerable but not determined		—
F	0.07	0.07	—

The virtual absence of CaO and the abundance of iron and aluminum oxides in these highly phosphatic rocks are of obvious significance. Microscopic study of these three samples shows that they too are volcanic rock and that two of them have been partly and irregularly phosphatized.

In specimens 3005-a and 3005-b, phosphatization has affected about half of the original rock; in 3005-c the original rock has not been phosphatized or altered to any appreciable extent. This rock, which may be considered also to represent the other specimens prior to phosphatization, is a porphyritic felsite; that is, a fine-grained crystalline volcanic rock, consisting essentially of quartz and potassic feldspar, with minor amounts of hematite. The fine-grained stony groundmass consists of tiny feldspar lathlike crystals, with quartz, and disseminated iron oxide; in this groundmass are large crystals of quartz with coarse feldspar and large grains of iron oxide. In the hand specimen the matrix is flesh-colored, the coarser quartz and feldspar whitish. The 0.44 percent P_2O_5 reported in the analysis is somewhat more than is usual in rock of this type, which rarely exceeds 0.25 percent P_2O_5; the analysis was probably made on slightly phosphatized rock.

The other two specimens—3005-a and 3005-b—outwardly resemble the unphosphatized rock, although they are more porous and have a semiglazed aspect. The larger quartz crystals are still visible, but the fine-grained groundmass is largely replaced by obscurely crystallized phosphatic material, presumably replacing feldspar.

PROBABLE ORIGIN.

The high phosphate content of the near-surface rocks is probably due to alteration of the fresh rocks by phosphatic solutions derived from deposits of bird or bat guano. Numerous writers have described similar occurrences of igneous rocks that have been phosphatized by guano deposits, resulting in deposition of iron-aluminum phosphates.[2] Even though there is now little or no evidence of guano along the cliff face or even in the crevices and caves, it can be easily supposed that in the remote past large numbers of birds or bats used this prominent hill, which is relatively near the ocean, as a roosting and nesting place. Subsequent ages of rain wash would have removed the resultant guano deposits, leaching their contents of phosphate and redepositing it by alteration of the surface rocks, large parts of which later broke off and joined the talus piles at the foot of the cliffs.

It is suggested that the process of phosphatization begins by the reaction of phosphoric acid on feldspar, essentially:

$$2KAlSi_3O_8 + 2H_3PO_4 \rightarrow 2AlPO_4 + 6SiO_2 + 2KOH + 2H_2O.$$

In the presence of the phosphate ion, the extremely insoluble aluminum phosphate would form, ensuring practically complete fixation of all P_2O_5 available in the guano as variscite or a similar compound, with release of active alkali as indicated. Silica would likewise be released from the feldspar; chert has frequently been observed associated with secondary phosphate of similar origin in other places. There are also to be considered compounds of the minyulite-leucophosphite type, potassium aluminum-iron phosphates, which form in the presence of strong alkalies, but hydrolyze to form the simple aluminum-iron phosphates.

CONCLUSIONS.

The conclusion is inescapable that the Gruta y Cerro Arrequita deposit, though of interest from the standpoint of genesis, has little or no present commercial value. First, the phosphate is almost entirely in combination with aluminum and iron. No process, feasible under present economic conditions, for making the P_2O_5 in such combination soluble, hence available to plants, is known. Second, the work on the samples collected to date shows conclusively that the phosphatic material is a near-surface feature, hence is sporadically distributed and extends only a few feet in depth at the very most.

However, it should be noted that the Japanese appear to have utilized iron-aluminum phosphate deposits, and under special economic conditions, it is possible that similar material may again become usable. One source for this statement is a paper that appeared in 1933, by Fujimaro Yamanari (11). In it appear the following data:

From 1918 to 1925 an average of about 2,000 tons a year of tri-calcium phosphate was produced from Kita Daito, an island of the Okinawa group, ceasing when the deposit was exhausted. However, beginning with 1919, by 1931 some 172,000 tons of aluminum phosphate had been mined.

[2] See bibliography at end of paper.

The aluminum phosphate is an alteration product of pumice; mineralogically it is said to belong to the turquoise group. Analyses of the ore have a composition (four samples):

P_2O_5	33.33%–43.75%
Al_2O_3	18.56%–32.73%
Fe_2O_3	4.69%–21.19%
SiO_2	0.38%–10.71%
CaO	,25%– 8.20%
Ign.	8.10%–15.00%

The composition of the pure phosphate closely approximates variscite ($AlPO_4 \cdot 2H_2O$), or barrandite $(Al,Fe)PO_4 \cdot 2H_2O$.

The aluminum phosphate was utilized by electrolyzing it to obtain elemental phosphorus for making matches; and, after roasting at 500°–600° C, as fertilizer. The roasting is said to make the phosphate soluble in citric acid; the roots of vegetation are said to secrete this acid, thus dissolving the phosphate.

A second source of information is an English translation of a typescript monograph on (Japanese) Phosphate Ore, by Yawato Aso, dated 1940. In it, Aso says:

> Aluminum phosphate is the pulverized product of the sintered aluminous phosphate ore which is made by heating the ore for 50 minutes at about 600° C. The reaction of sintering removes the moisture and adsorbed water and weakens the combining power of alumina and iron oxide with phosphoric acid, and also increased the porosity so as to increase the solubility without changing the composition of the ore. The absorption of sintered aluminum phosphate ore by plants is chiefly due to hydrolysis and its efficacy as a fertilizer depends on the amount of contained water. . . .
> In 1919 . . . no one was able to utilize rich (ferro-aluminous phosphate ore) in Japan. On the other hand, in U. S. A. the aluminous phosphate from Redonda Island of the West Indies was utilized for the manufacture of phosphate fertilizer and was continuously used for about 30 years up to 1888 when large deposits of phosphate ore were found in Florida and Tennessee. At the close of the 19th century several processes for the utilization of this ore were announced but none of them was commercialized owing to lack of knowledge on economical or practical problems. . . . The most successful usage of this ore is for the extraction of phosphorus. . . . In 1931 when Swedish International Match Corporation which had conquered the world's phosphorus industry, attempted to dominate the Japanese match industry and transfer the industrial equipment to China, what had resisted this strategy and contributed to the present match industry of Japan was really the existence of this aluminous phosphate ore in Japan.

It is possible that a heating process may render insoluble iron-aluminum phosphate usable to some extent as fertilizer; it is also possible that part at least of the virtue of such fertilizer may lie in the presence of soluble calcium phosphate, with which the Okinawa iron-aluminum phosphate is associated.

ACKNOWLEDGMENTS.

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1952, by Eckel and who accompanied him in the field. Specimens collected by Eckel at that time, as well as other samples that were submitted earlier by Dr. Walker to the Department of Agriculture, were studied in the laboratory by Milton. The writers are also indebted to Dr. W. L. Hill, Principal Chemist, and Mr. Robert M. Magness, Chemist, U. S. Department of Agriculture, for analytical data, to Mr. J. M. Axelrod, of the U. S. Geological Survey, for X-ray study of the specimens, and to Mr. Delos E. Flint of the U. S. Geological Survey for the references to Japanese utilization of non-aluminum phosphate.

U. S. GEOLOGICAL SURVEY,
DENVER, COLO. AND WASHINGTON, D. C.
April 8, 1953.

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Numerous writers have described occurrences of igneous rocks that have been phosphatized by solutions that have reacted with guano of birds or other vertebrates (bats, chiefly, but also rabbits, etc.), resulting in iron-aluminum phosphate deposits. A few papers describing such occurrences are listed below:

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METAMORPHIC DIFFERENTIATES IN THE BLACKBIRD MINING DISTRICT, LEMHI COUNTY, IDAHO.[1]

WAYNE A. ROBERTS.

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ABSTRACT.

Quartz pods and quartz veins devoid of economic minerals occur in the cobalt-copper mineralized Blackbird mining district in Lemhi County, Idaho. These barren quartz bodies are found in regionally and thermally metamorphosed rocks of the Yellowjacket formation (Belt series) of Precambrian age and are believed to be derived from the enclosing quartz-biotite and quartz-biotite-garnet-chloritoid schists by metamorphic differentiation. Other rocks that possibly are products of metamorphic differentiation are discussed.

Two zones of regional metamorphism are recognized, a biotite zone and a garnet zone. Contact metamorphism associated with the granitic intrusive rocks of the Idaho batholith is recognized adjacent to the batholith.

INTRODUCTION.

THE Blackbird mining district, Lemhi County, Idaho (Fig. 1), is one of the two or three most important cobalt-producing districts in the United States. Geologic studies of the district by the U. S. Geological Survey have been in progress since 1942, and studies in adjacent areas are continuing under the supervision of J. S. Vhay. The geology and ore deposits have been described in detail by Vhay (4).[2]

[1] Publication authorized by the Director, U. S. Geological Survey.

[2] Numbers in parentheses refer to Bibliography at end of paper.

The present paper describes the occurrence of certain quartz bodies, barren of economic minerals, that are believed to have been formed by metamorphic differentiation. The similarity of these barren quartz bodies to ore-bearing quartz bodies has led prospectors and miners to considerable small-scale exploration by pits, adits, and trenches. Similar barren quartz

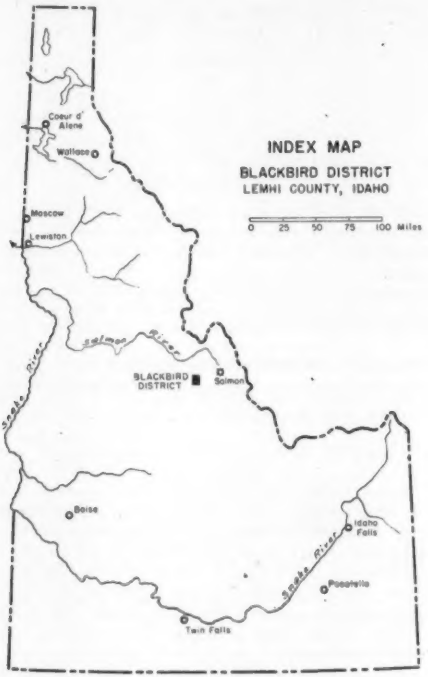

FIG. 1.

bodies may occur in other mining districts where reconstituted schist is the country rock. A knowledge of the origin of these bodies may therefore aid the prospector in better directing his exploration work.

ACKNOWLEDGMENTS.

The writer wishes to thank J. S. Vhay, R. A. Weeks, R. W. Chapman, R. E. Wallace, and W. B. Myers for valuable suggestions and criticisms. Mr. Vhay's unpublished geologic data have been used freely in this paper to provide basic information needed outside the areas mapped by the writer.

GEOLOGIC SETTING.

The oldest rocks in the Blackbird district are schists and quartzites of the Yellowjacket formation (Belt series) of Precambrian age. The minerals of these rocks have been completely reconstituted to quartz and biotite, with muscovite, garnet, chloritoid, and, at some localities, minor amounts of chlorite, alkali feldspars, hornblende, and cordierite.

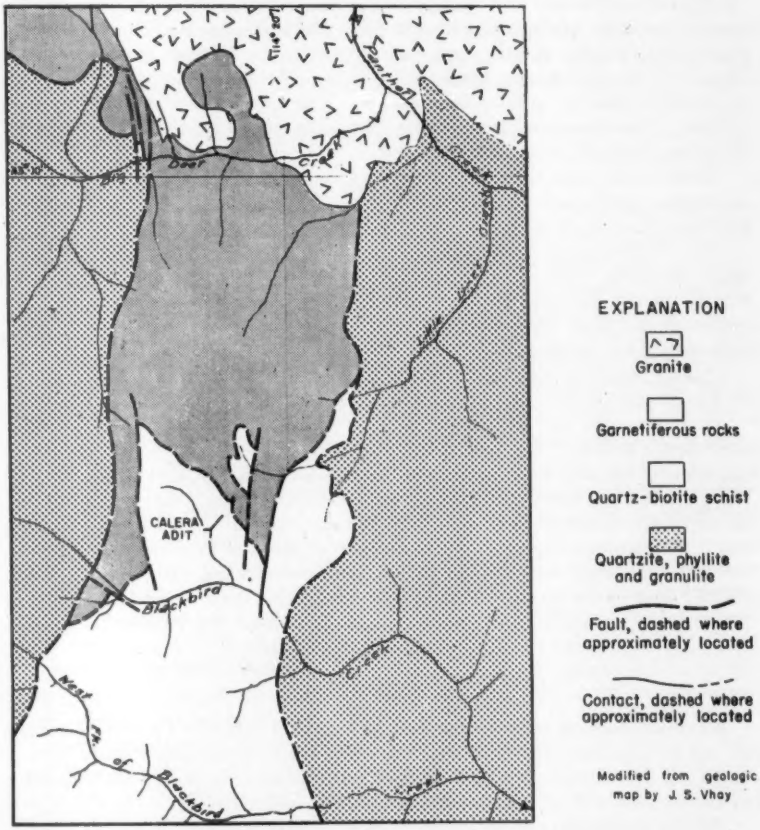

Figure 2

GENERALIZED GEOLOGIC MAP OF PART OF BLACKBIRD DISTRICT

The Yellowjacket formation has been folded into northward-plunging folds. The quartz-biotite schists and the garnetiferous schists have been more intensively deformed than the adjacent sediments. The folds are tight and overturned locally with crumpled bedding at the crests of anticlines and the troughs of synclines. There has been minor thrusting approximately along the axial planes of some of the tighter folds. Axial-plane cleavage is well developed locally in the more schistose beds.

The metasedimentary rocks are cut by metamorphosed basic dikes. The minerals of some of the altered basic dikes are albite, biotite, zoisite, glaucophane, hornblende, chlorite, and some carbonates. Other so-called basic dikes are now principally biotite with some albite and, locally, carbonates, muscovite, chlorite, quartz, and zoisite. The carbonates are calcite and siderite. The metamorphism of these dikes appears to be due to hydrothermal alteration, thermal metamorphism, and autometamorphism.

Shear zones, later than the folding and the basic dikes, cut the schists and quartzites; a cleavage parallel to the shear zones, called slip-shear cleavage by Vhay (4), locally masks or destroys the axial-plane cleavage.

The Yellowjacket formation was intruded by the granitic rocks of the Idaho batholith (Fig. 2). No evidence to establish the age of the batholith relative to the shearing has been noted. This batholith was probably the source of the heat that thermally metamorphosed some of the regionally metamorphosed sedimentary rocks.

Quartz prophyry dikes also cut the Yellowjacket formation. These dikes are fine-grained and contain phenocrysts of quartz, alkali feldspars, and biotite.

A garnet zone and a biotite zone of regional metamorphism are recognized in the schists. The garnet zone overlies the biotite zone, and the contact between the two zones appears to be a thrust fault that dips gently north. The garnetiferous rocks (Fig. 2) are exposed between the Idaho batholith on the north, the biotite zone on the south and east, and the phyllitic rock on the west. The eastern exposed limit of the garnet rocks is in part a northward-trending, high-angle fault and in part a northwest-dipping thrust fault. The western limit of the garnet rocks is a high-angle northward-trending fault to the south and a northward-dipping thrust fault near the batholith. Many later high-angle faults cut all the rocks in this district.

METAMORPHISM.

Metamorphism of rocks of the Belt series in the Blackbird mining district has not been studied in detail, and, therefore, the metamorphic history is incompletely understood. Additional studies of the metamorphism are planned, but the present state of information is herewith summarized.

All the sedimentary rocks of the area have been metamorphosed to phyllites, schists, granulites (decussate rocks), or quartzites. Regional metamorphism and contact metamorphism adjacent to some of the basic dikes and the Idaho batholith have been recognized. In addition to the metamorphism, considerable alteration and mineralization by hydrothermal solutions has occurred. The regional metamorphism probably preceded contact metamorphism caused by the intrusion of the Idaho batholith to the north and west.

Regional Metamorphism.—The first process of metamorphism of the Yellowjacket formation was possibly partial recrystallization related to pressures and temperatures accompanying deep burial of the sediments.

After deep burial, rocks of the Belt series were subjected to compressional forces that produced the folding of the region. The compressional forces have produced tightly folded and crumpled schists with associated thrust faulting roughly in the axial planes of some of the folds, and, in some places, metamorphic zonation of the rocks can be established. Two zones are recognized, a biotite zone and a garnet zone. The distribution of these zones is shown in Figure 2. Axial-plane cleavage can be recognized at many localities, although it is destroyed in other places by the later formation of slip-shear cleavage.

In the biotite zone the rocks contain, in addition to quartz and biotite, some muscovite and alkali feldspars. These rocks may be considered as a biotite zone of regional metamorphism.

The garnet zone occurs between the granite and the biotite zone, but appears to be thrust over the biotite zone; no gradational contact between the biotite and garnet zones has yet been recognized. The garnet zone contains in addition to the ever-present quartz and biotite a poikiloblastic red garnet between almandite and spessartite in composition, poikiloblastic chloritoid, some muscovite, chlorite, alkali feldspars, and, locally, hornblende. The garnet and chloritoid appear to be restricted to the more schistose beds; garnet occurs more commonly in the rocks high in mica, chloritoid in the more siliceous rocks. In places, garnet and chloritoid occur together.

During regional metamorphism quartz bodies are believed to have been formed by metamorphic differentiation. These bodies occur as pods, as a-c and b-c (Billings, 1) quartz veins, and as other veins that cut the schists. The formation of these bodies by metamorphic processes is discussed under "Quartz Pods and Quartz Veins."

Contact Metamorphism.—Contact metamorphism is believed to be later than the regional metamorphism. The evidence of dynamic metamorphism has been destroyed locally by the intrusion of the batholith. Contact metamorphism is evident in the field only locally. Microscopic examination of thin sections, however, disclosed cordierite in decussate quartz-biotite rocks near granitic rocks of the Idaho batholith and in a thin section cut from diamond-drill core in the biotite zone.

A roof pendant of the schists of the Blackbird district just north of Big Deer Creek contains red garnets up to 6 inches in diameter. No chloritoid was found in the schists here; however, these rocks have not been studied sufficiently to say positively that chloritoid or the thermal-metamorphic alteration products of chloritoid are entirely absent. At this locality some crystal faces of the garnets are very clear and brilliant and probably are the result of recrystallization. It is believed that the increase in size of the garnets and the absence of chloritoid is due to increased temperature of the schists coincident with the intrusion of the batholith.

Poikiloblastic hornblende (?) now altered to chlorite occurs in schists adjacent to the basic dikes. The metamorphism of the basic dikes or some of the rocks adjacent to the basic dikes has not yet been studied.

Mineral Alterations.—There is little evidence that retrograde metamorphism was important in this district. Some mineral alterations did occur, however, in the garnet zone. G. M. Sowers examined thin sections from the Blackbird district in 1945 and reported that some biotite has altered to chlorite and that some of the garnets, especially at the rims, have altered to biotite and muscovite. Some postchlorite muscovite was also noted. Locally, chloritoid has altered to muscovite, biotite, and chlorite. This alteration may be the result of thermal metamorphism. Chlorite and biotite have developed from poikiloblastic hornblende. Some of the chlorite seen in the thin sections was determined to be prechloritoid by Sowers, and, therefore, this chlorite is probably a remnant of the early chlorite stage of regional metamorphism.

METAMORPHIC DIFFERENTIATES.

Many of the quartz bodies in this district may be the result of metamorphic differentiation. The absence of valuable metal content is most easily explained if the barren quartz pods and veins were formed by metamorphic processes, and not as a result of later hydrothermal mineralization. Many of these quartz pods and veins are located as much as a mile from any known cobalt deposit. The distribution of the quartz pods is related to the regional metamorphism rather than to the metalliferous deposits of this mining district.

Quartz Pods and Quartz Veins.—Quartz pods are scattered throughout the biotite zone and garnet zone of regional metamorphism. The pods are common and are exposed in many prospect pits, small adits, and outcrops. Many of the pods are enclosed, or partly enclosed, in a sheath of biotite. This biotite is a dark gray to dark green that appears to be black megascopically and is not so well oriented as the biotite in the country rock. Locally, this biotite is oriented parallel to the adjacent boundary of the quartz pod. In some specimens the biotite is decussate and is the only mineral present. The bulk composition of the quartz pods and the biotite sheaths appears to be about the same as the composition of the enclosing country rock. The pods occur near the crests of folds, in sheared rock, and in schists where no structure other than axial-plane cleavage is noted. Several pods were found beneath the crests of small overturned anticlines in schist (Fig. 3). The overlying quartzite bulged out, leaving ample space for the pod.

The contacts of these pods are locally slickensided and coated with biotite parallel to the surface of the pods, with lineations on these slickensides in the plunge direction of the folds. This would seem to indicate movement of the pod, after formation, along the plunge direction of the folds. Elsewhere the contacts are irregular and appear to be replacement contacts with the enclosing schistose rocks. The position of these quartz pods underneath the crests of anticlines, as well as the slickensides on some of the pods, might indicate that some of the pods were formed during folding.

Quartz veins and stringers are at least as widespread and as numerous as the quartz pods. Two types of quartz veins occur along joints that are

perpendicular to the axial plane of the folds; i.e., along a-c joints with moderate dips, generally to the south, and along b-c joints with shallow northerly dips. Quartz pods and lentils are found elsewhere along faults as discontinuous veins. Other quartz veins, which may be attributed to metamorphic differentiation, were noted cutting the schists. The quartz veins that cut the schists are neither a-c nor b-c veins. Locally, they contain coarse crystals of chloritoid 1 to 2 inches in diameter.

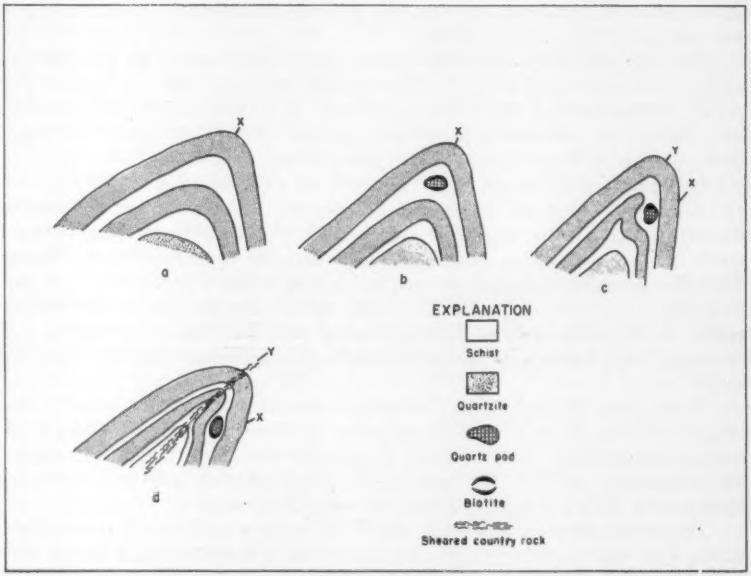

FIG. 3. Probable development of Quartz pods during folding. a. Formation of folds and development of schists; X indicates axial plane of fold at this stage. b. Continued compression. Quartz pod formed in position of minimum pressure. c. Further folding of rocks. Quartz pod rotated to a position beneath crest of anticline; reference point X indicates extent to which old axial plane has been rolled; Y indicates axial plane at this stage of folding. d. Rocks so folded that anticline overturned. Quartz pod well beneath crest of anticline. Shearing along axial plane has developed as last stage of compressional forces. Y indicates axial plane of fold; reference point X indicates extent to which axial plane of a and b has been rolled.

The mineralogy of the quartz pods and veins is relatively simple, and the composition is very nearly that of quartz-rich reconstituted argillaceous sandstones. The schists are composed essentially of quartz and biotite with garnet and chloritoid and minor amounts of muscovite, alkali feldspars, and hornblende. Quartz probably constitutes about 95 per cent of the material in the pods, with biotite, chloritoid, garnet, and probably albite as the

minor components. The biotite in the pods is mostly dark green in contrast to the dark brownish-gray biotite of the country rock. The chloritoid is a rare constituent of the pods, but where seen it occurs as well-crystallized, dark-green plates rather than as the poikiloblastic anhedral blobs common in the schist. The albite, where seen in thin sections, is clear and untwinned and, because it is difficult to distinguish from the quartz, may be present in greater concentrations than have been detected. The minerals of the quartz bodies are generally coarsely crystalline and the biotite is commonly decussate. The a-c and b-c quartz veins are generally short and without conspicuous amounts of any other minerals.

The principal differences between the quartz pods and veins and the enclosing schistose rocks are: (1) The quartz pods are richer in quartz and poorer in biotite than the enclosing schists. (2) The quartz pods contain decussate biotite and interlocking quartz grains, whereas the schists are composed of aligned biotite and granular, recrystallized quartz.

The quartz pods at and near the crests of anticlines and the troughs of synclines and the a-c and b-c quartz veins occupy places of minimum pressure during folding, and are believed to have been formed by migration and redeposition of silica in solution while rocks were stressed by deformational forces. The silica probably migrated to rock under less pressure much as quartz has migrated to pressure shadows behind rigid equidimensional grains in schistose rocks. The quartz pods in shear zones and in schist where no folding was noted probably formed in places also under less pressure than the adjacent rocks.

No evidence has been found to indicate the direction of movement of the silica; however, the silica probably migrated in directions dictated by the local physical environment rather than in an absolute direction either up the flanks of the folds or laterally. In general, the silica probably migrated from the flanks of the folds toward the crests and troughs of the folds.

The preservation of crystalline chloritoid in these pods would seem to indicate that these pods were not formed by high-temperature solutions but rather that the ions in a solution below the temperature at which chloritoid is destroyed could migrate freely to a nearby place of minimum pressure or shearing stress. The quartz and biotite apparently crystallized freely.

These quartz pods were probably formed by the migration of the silica in solution to volumes under less pressure or less shearing stress than the surrounding rocks. Although the evidence is not conclusive, metamorphic differentiation of the materials from the surrounding rocks seems more likely than magmatic emanations as a source for the materials present in the pods and veins.

"Biotite Dikes."—Several crosscutting "dikes" composed entirely of dark brownish-gray biotite that is megascopically identical with the biotite of the country rock were noted cutting the bedding at one locality. The dikes appeared to be free of any mineral other than biotite. A fine hairline fracture splits each dike, and the biotite flakes of the dikes are parallel to the fracture. The biotite of the country rock at this locality is roughly parallel to the bedding.

The biotite dikes noted may or may not have formed by metamorphic differentiation; however, they were probably formed consequent to circulating solvents. The biotite may have been concentrated by removal of the more soluble quartz, or it may have been deposited in fractures. Subsequent minor movement along the fractures could account for the attitude of the biotite flakes. The uneven surface of the fractures probably left room for circulating solvents to remove the quartz, which might have been crushed and therefore more soluble than the quartz in the adjacent country rock.

Laminated Metamorphic Differentiates.—Alternate layers of quartz and biotite occur in shear zones that cut the schistose rocks. Some of these layered rocks exhibit a braided structure of quartz lenses surrounded by biotite. Some of these layers are uniform for distances up to several feet. These layers differ from bedding in relatively undisturbed localities principally in the concentrations of the minerals in the layers. Generally, the laminae representing bedding consist of quartz and biotite layers where the biotite content is different in adjacent layers. The biotite content in the bedding laminae ranges from about 5 per cent to 40 per cent. The biotite content in the layered rocks of the shear zones is either about 0 to 5 percent or 90 percent to 100 percent.

It is believed that this shearing, or banding, is due in part to metamorphic differentiation and in part to differential mechanical movement.

Comparison of the Barren Quartz Bodies and the Mineralized Quartz Bodies.—The presence of quartz in the Blackbird district does not necessarily indicate the presence of valuable metallic minerals. Some of the quartz described in this paper has been mineralized by later hydrothermal emanations. Vhay believes that the known cobalt-copper deposits are the result of hydrothermal solutions probably associated with the late phases of the Idaho batholith. Although both the country-rock schist and the metamorphically derived quartz bodies have locally acted as host rocks for the mineralizing solutions, all the known mineralized quartz bodies show at least one of the following indications of the former presence of ore minerals: (1) Cobalt or copper bloom; (2) green and yellow-green stained porous quartz; (3) brown to dark reddish-brown gossans. A more detailed description of the indications of ore minerals in the Blackbird district is presented in Vhay's report (4).

Thus, prospectors in mining districts, particularly the Blackbird district where the country rock is a quartz-rich schist, should look not only for quartz but for other indications of the former presence of ore minerals before extensively prospecting a quartz body.

CONCLUSIONS.

The quartz pods, the a-c quartz veins, and the b-c quartz veins were formed in low-pressure lentils much as quartz migrates to the strain shadows behind rigid equidimensional grains in schistose rocks. The quartz in these bodies migrated from the enclosing schistose rocks. The other veins noted in this area that were probably formed by metamorphic differentiation are not

clearly in pressure minima; however, these were probably formed in places under less pressure than the surrounding rocks.

No evidence has been collected to limit the possible extent or direction of migration of the silica. The silica was probably more mobile than other mineral components, although some migration of other components was necessary to form the biotite in clean recrystallized form. Some silica was probably introduced into the rocks of the Belt series here during one of the later periods of mineralization. It is concluded, however, that most of the quartz bodies in this area were derived by metamorphic processes from the surrounding quartzose rocks.

No definite age can be placed on the quartz bodies. The first quartz bodies probably were formed during folding. The age of the latest quartz bodies is not known.

The quartz pods, the a-c and b-c quartz veins, the quartz-albite veins, and the biotite "dikes" are thought to have formed either by solution and redeposition or by removal of quartz in the quartz-biotite schists; i.e., quartz was redistributed according to Eskola's (2) solution principle of metamorphic differentiation as cited by Turner (3). This conclusion is based on the following evidence: (1) The distribution of the quartz pods and veins irrespective of known ore deposits; (2) the simple mineralogy of these bodies; (3) the similarity of mineralogy of these bodies and the enclosing rocks; (4) the presence of most of these bodies in spaces that probably were in pressure minima during folding; (5) the presence of chloritoid, garnet, and untwinned albite in the quartz bodies; (6) the absence of cobalt and copper minerals from from most of these bodies. This evidence is at best circumstantial, but it does seem to indicate that these quartz bodies were formed by metamorphic rather than by magmatic processes.

U. S. GEOLOGICAL SURVEY,
SPOKANE, WASH.,
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GEOLOGY AND GROUND-WATER CONDITIONS IN THE LOWER VALLEY OF THE RIO ELQUI OF CHILE.[1]

PAUL H. JONES.

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ABSTRACT.

The stability of the agricultural economy of the valley of the Río Elqui depends primarily upon irrigation-water supply. Water rights of the landholders along the Río Elqui exceed the stream flow in dry years, and the "water security" has been estimated by engineers of the Frederick Snare Corp. to be about 65 percent. Irrigation with ground water so far has been limited to the diversion of spring flow; there has been no development of large ground-water supplies by pumping.

The agricultural productivity of the region could perhaps be doubled by (1) raising the water security of land now irrigated in the valley to 100

[1] Prepared by the Geological Survey, United States Department of the Interior, in cooperation with the Corporación de Fomento de la Producción, Republic of Chile.

percent and by (2) providing water supplies to irrigate all or part of the 12,000 hectares (29,700 acres) of arable land in the Lagunillas Basin, a desert area extending southward from and merging with the "100-meter" (330-foot) terrace of the lower valley.

Investigations of ground-water conditions in the valley have been in progress since September 1949. Three test holes are now (April 1950) being drilled under most difficult conditions. None of these have reached bedrock although one is about 140 meters (460 feet) deep. One well has been test-pumped at a rate of about 58.5 liters per second (930 gallons a minute) with 3.92 meters (less than 13 feet) of drawdown. After nearly 5 days of pumping at an average rate of 38 liters per second (about 600 gallons a minute) the water level in this well recovered to the original static level less than 10 minutes after pumping stopped, indicating that recharge of the aquifer is occurring.

Some 60 pits have been dug in the lower valley for the purpose of water-level observation, but only about 4 months of record is available.

Results of preliminary studies of the ground-water conditions in the lower valley of the Río Elqui indicate that proper development of the aquifers that underlie the flood plain of the river will surely accomplish the first objective given above, that of increasing the water security to 100 percent; and should go far toward accomplishment of the second, that of increasing the agricultural productivity through irrigation in the Lagunillas Basin.

INTRODUCTION.

Location and General Features.—The valley of the Río Elqui lies in the northern part of the Province of Coquimbo in the "Norte Chico" of Chile, an area of rugged mountains that extends eastward from the sea to the International Boundary. The valley of the Río Elqui extends eastward from the Bay of Coquimbo along the 30th parallel, south latitude, which it crosses twice in its course (Fig. 1). The city of La Serena (population about 30,000 in 1950) is on a low alluvial terrace on the southern side of the valley about half a mile from the Bay of Coquimbo, where the Río Elqui enters the sea. Vicuña (population about 2,000), about 65 km up valley from La Serena, is the principal inland town. The seaport of Coquimbo (population about 25,000) is at the southern extremity of the Bay of Coquimbo on the northeastern flank of a low mountain of pink granite that forms a peninsula protecting the harbor. Coquimbo is about 12 miles southwest of La Serena, and the two cities, which lie on the Pan American Highway, are joined by an excellent paved road and a narrow-gage railroad.

The lower valley is traversed by a good gravel or dirt road and a narrow-gage railroad as far up valley as Rivadavia. It is 16 hours from La Serena to Santiago by rail motor coach and about 2½ hours by air.

Previous Investigations.—The general geology of the region is discussed by Juan Brüggen (1),[2] and the areal geology is shown in part on the geologic map of Chile (2). A short paper by Dr. Ing. Ricardo Fenner R. (3) describes the results of subsurface studies of the geology at the Algarrobal dam site near Rivadavia, about 90 km from the sea. George C. Taylor, Jr., of the Ground Water Branch, United States Geological Survey, made reconnaissance

[2] Numbers in parentheses refer to Bibliography at end of paper.

studies of the ground-water resources of five areas in the Province of Coquimbo in October 1946, and again in October 1947. His reports (6) summarizing the investigations have aided the writer materially in his efforts to analyze ground-water conditions in the valley of the Río Elqui.

Results of geologic studies by Dr. A. E. Sandberg and Charles R. Kolb of the Frederick Snare Corp. have been made available to the writer.

Purpose and Scope of the Investigation.—In April 1949 the Chilean Development Corporation (Corporación de Fomento de la Producción de Chile) selected three major irrigation projects for intensive study and employed the Frederick Snare Corp., consulting engineers of New York, to investigate and report upon the engineering feasibility and the cost-benefit ratio of each project. Each of the three proposed projects involved the construction of a large dam and reservoir, high-level canals of large capacity, and smaller diversion canals.

Investigations in the valley of the Río Grande (80 km s of the Río Elqui) for the proposed dam at La Paloma, and in the valley of the Río Elqui for the proposed dam at Algarrobal, included the drilling of a number of exploratory holes in the flood plains of those streams for foundation studies. The deepest boring at the La Paloma site was abandoned in bedrock at a depth of 75 m and the deepest boring at the Algarrobal site was abandoned in alluvium at a depth of 95 m. The alluvium at the two dam sites is much the same in texture. It is generally a heterogeneous mixture of clay, sand, gravel, and boulders. Zones of very permeable sand and gravel were noted in the near-surface alluvium (upper 12 to 14 m) at La Paloma and from the surface to a depth of 5 to 7 m at Algarrobal. Several zones of permeable alluvium were penetrated at depth in both places.

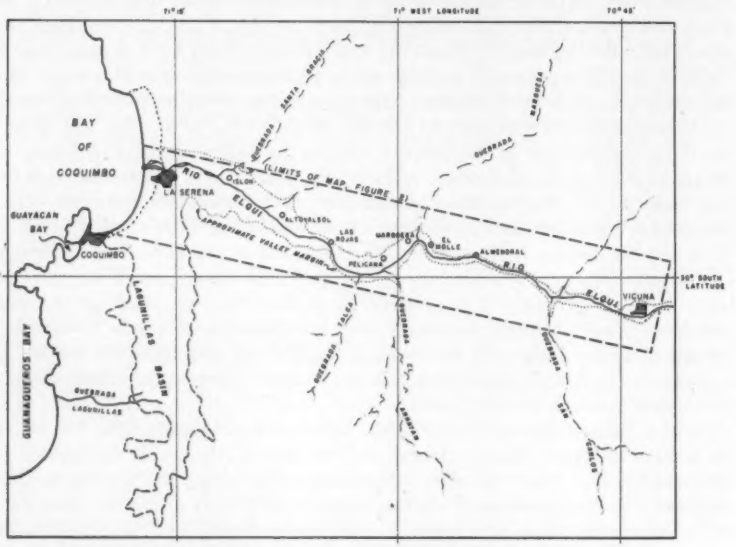
At La Paloma the water table in the alluvium was no more than 3 m below the level of the flood plain in December 1949, and at Algarrobal the conditions are comparable. Water-flooding difficulties in excavating the permeable alluvium prior to the placement of the impermeable earth core of the proposed dam at La Paloma have been anticipated by the Frederick Snare Corp. (Río Grande Project Report, part VII–2f). The Corporation's recommendation for abandonment of the Algarrobal dam site is based in part upon the expense entailed in construction of an upstream blanket of clay to prevent excessive seepage below an earth-fill dam some 95 m high, resting upon permeable water-saturated alluvium as much as 95 m thick.

Because of the lack of good locations and the danger of rapid siltation, no supplemental surface-water storage for irrigation in the valley of the Río Elqui is considered feasible.

The valley is intensively cultivated and all surface waters available in the form of river flow are now appropriated by the landholders. In fact, the supply is oversubscribed and the irrigation-water security is now rated by the engineers of the Frederick Snare Corp. at about 65 percent. Much of the land now irrigated is not the best available and in many places the slopes exceed 45°. Hundreds of acres of nonirrigated land in the valley are suitable for farming except for the lack of water; and in the broad, flat expanse of the Lagunillas Basin, which extends southward from the high terraces on the

southern rim of the lower valley, there are no less than 12,000 hectares (29,700 acres) of good to excellent arable land now desert for lack of water.

It was not surprising, therefore, that irrigation engineers and engineering geologists from the United States, employed by the Frederick Snare Corp. and assigned to the investigation of the Algarrobal dam site, conceived the idea that moderate, if not large, ground-water supplies might be available for irrigation from wells tapping the thick deposits of permeable alluvium that underlie the flood plain of the Río Elqui. As additional information on conditions at



MAP OF NORTH-CENTRAL PART OF PROVINCE OF COQUIMBO, REPUBLIC OF CHILE

FIG. 1. Sketch map of portion of north-central part of Province of Coquimbo, Republic of Chile.

Algarrobal became available and tended increasingly to discredit its feasibility as a dam site, the evidence in favor of ground-water development in the valley increased. In September 1949 the drilling rigs and personnel assigned to the dam site investigation were relocated down valley at three test sites, and an intensive study of the ground-water conditions was begun.

The present writer was detailed to make a study of the ground-water conditions, as a result of a request received by the Geological Survey from the Government of Chile in December 1949. A tour of duty in Chile from March 8 until April 8, 1950, provided the data upon which this paper is based.

Acknowledgments.—Most of the detailed factual information presented in this report was obtained through the courtesy of members of the staff of the

Santiago, Chile, office of the Frederick Snare Corp., of which Henry F. Stubbs is the project manager. Dr. A. E. Sandberg, consulting geologist, and his assistant, Charles R. Kolb, who directly supervised all test drilling in the valley by the Frederick Snare Corp., were most helpful. Scott Stubbs, field assistant engineer for the corporation, supervised pumping tests and collected and analyzed the pumping-test records, well-construction records, and quality-of-water data. Harold Kidder, irrigation engineer, supervised study of plans for the development of ground-water supply and for the collection and distribution of well water. Others of the staff of the Frederick Snare Corp. included I. K. Landon, agronomist; Alberto Arretz, irrigation engineer, and Manuel Claro, hydraulic engineer, the latter two on loan from the Departmento de Riego, Republic of Chile.

Lewis C. Smith, irrigation engineer of the Frederick Snare Corp., New York office, who was primarily responsible for the beginning of the ground-water studies, has proposed several plans for ground-water development in the valley.

CLIMATE.

The climate of the region is arid, of the Mediterranean type. Nearly all the annual precipitation occurs during the winter months, from May to September. At La Serena, some 15 to 20 m above the sea, the average annual precipitation is about 160 mm (6.3 inches); but the precipitation in some years has been as low as 2 mm. Precipitation increases with altitude, and on the higher slopes of the mountains inland in the drainage basin of the Río Elqui it may be more than 750 mm (29.5 inches).

At La Serena most precipitation occurs as dewfall from heavy fogs. Inland it occurs as rain, except that above altitudes of 2,500 m (8,200 feet) snowfalls are common. Perpetual snowcaps blanket the highest peaks in the region.

The prevailing winds blow eastward (landward) but there is a pronounced diurnal cycle in wind velocity. The air over the Pacific Ocean is cooled by the Humboldt Current, which originates in the Antarctic and flows northward along the coast of Chile. The rugged, barren land warms the air during the day and convection currents in the high mountains result in strong west winds at midday in the east-west-trending valleys of the "Norte Chico." The wind begins to blow about 11:00 A.M. and by 2:30 P.M. is generally almost a gale. By 5:00 P.M. it is slackening, and by nightfall it is stilled.

In the valley the summer days are monotonously clear and at Vicuña even the winter days are so. Fog blankets the coastal lands and valley mouth on fall and winter mornings but it generally lifts by about 9:30 o'clock.

PHYSIOGRAPHY.

General.—The valley of the Río Elqui lies in the desert lands of the "Norte Chico" of Chile, a region of high mountains and narrow, deeply incised valleys. Although the topography is extremely rugged, sheer cliffs are not common because deep weathering has formed a thick mantle of talus on nearly every slope. The loose rubble lies in steep slopes and is ready to slide at the least

cause. The torrential rains that occur at intervals of several years usually have disastrous consequences.

The relief in the region within 25 to 30 km of the sea is in the order of 1,500 m, but inland at the longitude of Rivadavia the peaks rise to a common level about 3,600 m above the sea.

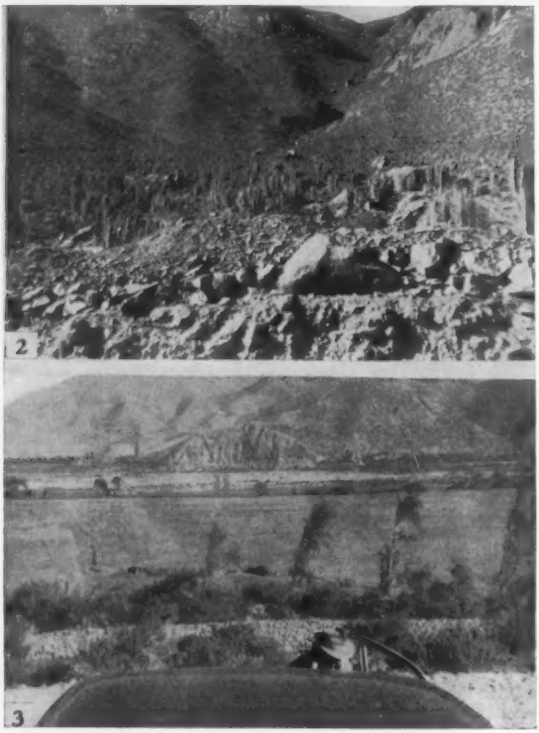


FIG. 2. View southward into a small quebrada from the Vicuna road west of Almendral.

FIG. 3. View westward across the valley toward the site of test well T–3 (La Calera).

To the east along the International Boundary the peaks along the crest of the Andes reach heights of about 6,000 m (20,000 feet). Cerro de Olivares is 6,254 m high; and Cerro las Tórtolas, about 131 km due east of La Serena, is 6,172 m high.

The Elqui Valley.—The mouth of the Elqui Valley where it joins the coastwise terraces along the Bay of Coquimbo is about 8 km wide. The flood plain is about 900 m wide at this point, and is flanked on each side by a series of

benches, or terrace remnants. To the west where the flood plain borders the bay it is a low marshland.

The most extensive terrace in the valley is on the southern margin, and it alone comprises more than half the valley width in this section. It lies at an altitude of about 100 m and extends eastward up the Elqui Valley and southward to merge with the floor of the Lagunillas Basin.

Up valley, the terraces become narrow and eventually disappear. In the vicinity of Las Rojas, about 20 km from the sea, no less than five distinct terrace levels are present, two above and two below the "100-meter" terrace mentioned above.

Where topographic maps are available and enable comparison of the slopes of the terraces, there is general parallelism between the terraces and the modern flood plain. The "100-meter" terrace slopes seaward at a rate of about 7 meters per kilometer (37 feet per mile), and the flood plain in the same reach (below Altovalsol) slopes seaward at a rate of 9 to 10 meters per kilometer (47 to 53 feet per mile).

In the lower valley below Marquesa, the dominant physiographic features are the terraces, but above that point the alluvial cones of tributary quebradas (Fig. 2) have a marked effect on the flood plain. The cones of alluvium move into the valley from the quebradas during rainstorms or rapid snowmelt. The ability of the river eventually to scour away and transport the cone materials down valley is everywhere demonstrated, but in the narrow sections of the valley the cones in some places are extended across the valley and dam the river for short periods.

The valley is bordered throughout its length by slopes that become steeper up the valley (Fig. 3). Above Vicuña the steepness of the canyon walls and the narrowness of the canyon are accentuated, and the rockslide is a dominant factor in flood-plain alluviation. The name "huracanes" has been applied to the large roaring hillside slides which, after even a light rainfall, deluge the flood plain with loose rock, sand, and mud.

A quebrada has formed a cone at the Algarrobal dam site, and it provides an excellent example of the relation between the flood plain and the cones. The Algarrobal cone moved completely across the flood plain in May 1934 when, according to eye-witness accounts, a natural dam some 8 to 10 m in height was formed. Although the rate of flow of the Río Elqui at that time and during the next 10 days was about 15 cubic meters per second (530 cubic feet per second), the dam was not overtopped because the impounded waters seeped through or under the barrier. A channel was blasted through it about 10 days after it formed, but it was not until 9 years later, in 1943, that a flood resulting from a summer thaw (a "deshielo") washed out the natural dam and spread the rock debris down the valley.

The maximum width of the valley (near the longitude of Islón) is about 7.5 km, and its minimum width below Rivadavia is probably less than 500 m. Above Marquesa the valley floor in few places is more than a few meters above the flood plain of the river (Fig. 4). At Almendral there is a low terrace remnant secure from floods. At Vicuña the valley broadens to a width of

about 2 km, and a prosperous farming area is situated on a low terrace at the foot of a southward-sloping cone.

A striking feature of the flood plain for the full distance from the Algarrobal dam site to the city of La Serena is its almost continuously smooth gradient. There is only a very slight flattening of the slope near the sea; the gradient is about 10 meters per kilometer (53 feet per mile) up valley from

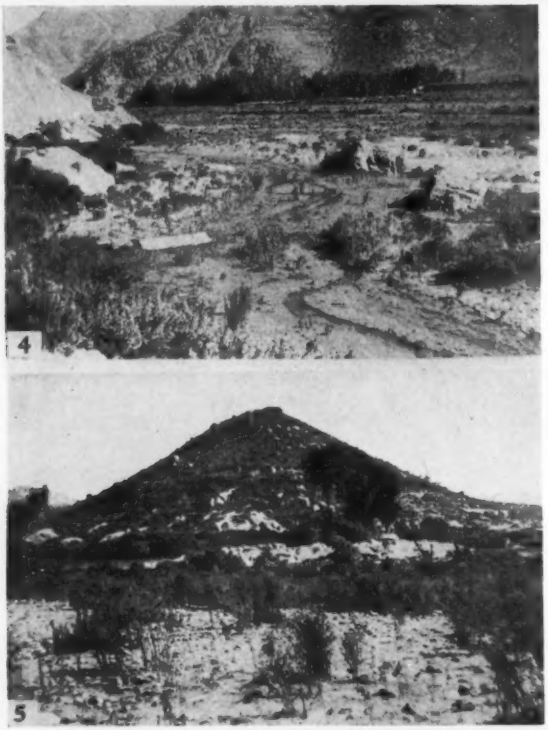


FIG. 4. View westward (down valley) from the southern margin of the valley west of Almendral. Note large boulders in flood plain and spring-fed brook in foreground.

FIG. 5. View southwest from the flood plain toward Puntilla Las Rojas, a granite spur showing flood scour.

Las Rojas (about 22 km from the sea), and about 9 meters per kilometer (47 feet per mile) down valley. It is apparent that valley width and the abundance of tributary-channel junctions have little or no effect on the slope of the flood plain.

Drainage.—The drainage of the valley is a closely knit system. Few quebradas tributary to the main channel are more than about 20 km long. As the

valley is essentially transverse to the axis of the major geologic structure of the region, many quebradas enter the valley almost at right angles. However, the extreme complexity of the bed-rock geology lends the drainage a pattern neither typically dendritic nor trellis.

Most of the tributaries other than the Río Claro and the Río Turbio, which are fed by snow melt in the summer and by rains in the winter, do not have perennial flow throughout their length. Many streams have permanent flow in their upper courses where they are fed by springs, and the alluvium commonly present in the channel is thin or absent, but in their middle and lower courses they are ephemeral. During the winter rains the ephemeral streams may become raging torrents, carrying flows of scores of cubic meters per second.

The largest tributaries that enter the lower valley of the Río Elqui are Quebradas Santa Gracia and Marquesa from the north and Quebrada Arrayan from the south.

The gradients of all the streams in the Elqui system are steep, generally in excess of 1 percent. However, the waterfalls generally present along such streams are absent in the lower valley because the thick alluvium contains no indurated strata.

GEOLOGY.

Studies of the geology of the valley of the Río Elqui made prior to this investigation are discussed in the introduction to this report. No detailed geologic mapping has been done.

Geologic work done by the writer was specifically directed toward an understanding of the ground-water conditions in the valley. Because no important ground-water supplies appear to be available from the consolidated rocks of the region, little effort was made to interpret the geology of the hard-rock terrane during the tour of duty. However, certain features of the regional geology have a close bearing upon the occurrence and movement of ground water, and it is for this reason that the following general discussion is presented.

Stratigraphy.—The oldest rocks in the region, as shown on the geologic map of Chile (2), are Lower Cretaceous or Upper Jurassic dark-gray to black porphyritic lava flows, characteristically interbedded with indurated tuffs and breccias. These extrusive rocks are a part of the widely known "Formación Porfirítica." The rocks occur in a narrow north-trending belt about 3 km wide, which crosses the valley just west of Islón, about 8 km from the sea, and forms the first range of low mountains east of La Serena. This range rises about 600 km above the sea.

On the north wall of the valley, mountains composed of other rocks of the "Formación Porfirítica," predominantly lavas, extend eastward almost without interruption to a point above Rivadavia, rising in higher and higher ranges for a distance of about 60 km. On the south wall of the valley the lava flows of the "Formación Porfirítica" extend from the mouth of Quebrada Arrayán eastward to Rivadavia with only one major break, near Vicuña.

Upper Cretaceous granite and granodiorite form the low coastal mountains north and south of the Bay of Coquimbo and extend inland along the north

wall of the valley a distance of about 5 km. On the south wall these granitic rocks are present from Islón, about 8 km inland, eastward almost to Quebrada Arrayán, a distance of about 19 km. These rocks form an area of rather low relief characterized by typically "round-shouldered" mountains. Figure 5, a view southward from the flood plain at Las Rojas, shows a spur of granite that projects into the valley.

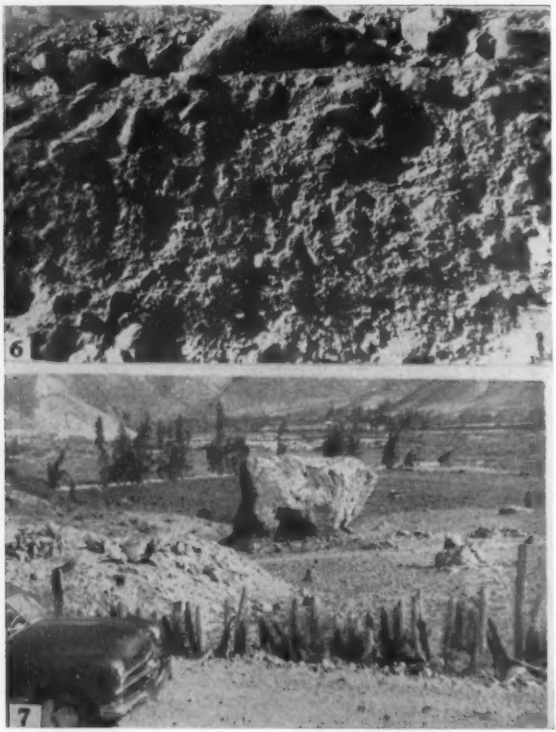


FIG. 6. Road cut through a typical quebrada cone in lava-flow terrane.
FIG. 7. Boulder on the south margin of the valley west of Almendral.

Granitic rocks underlie a roughly circular area about 5 km in diameter, centered at Vicuña.

Coastwise terraces underlain by Pliocene (?) clay, sand, and gravel interbedded with marine shells and marl occur south of La Serena, but the marine deposits are not known to extend inland more than a few miles.

Quaternary alluvium of clay, sand, gravel, and boulders forms the valley floor and marginal terraces, and is known to fill a channel scoured into indurated rocks as much as 140 m below the modern flood plain near Vicuña. The

base of the scour channel has not been reached by the drill. Cone deposits of poorly sorted clay and talus, including thin zones of water-laid sand and gravel (Fig. 6), occur near the mouths of the smaller quebradas tributary to the valley. Landslide alluvium derived from weathering products blankets the valley walls and commonly contributes to the marginal deposits. Boulders as large as a house (Figs. 4, 7) lie in the valley floor, resting in alluvium.

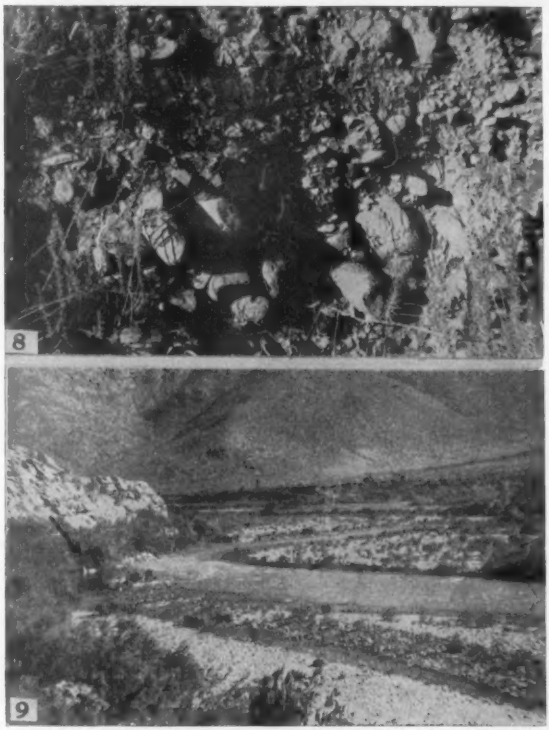


FIG. 8. Zone of permeable water-laid alluvium in a low terrace escarpment on the north side of the valley east of well T–3.

FIG. 9. View northwest across the valley showing the staff gage at Almendral.

The texture of the water-laid alluvium is generally favorable to the movement of ground water (Fig. 8). The alluvium derived from the weathered granitic rocks is typically coarser than that derived from the weathered lava flows and tuffs of the "Formación Porfirítica." The valley is generally broader where it crosses areas underlain by granitic rock than where it cuts through areas composed of the extrusive rocks.

From the sea up valley to the mouth of Quebrada Arrayán, a distance of about 29 km, the valley is relatively wide, and the slopes of the south wall, formed on granite, are less steep than the slopes of the north wall, formed on basaltic lavas. Above Arrayán, where the valley is flanked on both sides by lava flows, it narrows to a width of about 500 m and continues as a narrow canyon to a point a few miles below Vicuña. In the vicinity of Vicuña the valley crosses the small circular area of granitic rocks mentioned previously. There, it broadens conspicuously and the valley walls are less rugged. Above Vicuña, the valley again enters a terrane composed of lava flows, and the valley becomes a narrow gorge.

Above Rivadavia the two principal tributaries of the Río Elqui cross an extensive area of granitic rocks. The drainage basin of one of these, the Río Claro, is underlain almost entirely by granitic rocks. The contribution of detrital materials from granitic rocks has been sufficient to provide thick zones of permeable alluvium in the valley fill, in and downstream from the Claro Basin. This factor is of great importance in relation to ground-water movement in the alluvium, and in regard to well construction.

Information from drillers' logs indicates that the alluvium in the valley is not at all homogeneous in permeability. Zones of permeable sand and gravel are separated by zones of less permeable sand, gravel, and clay. However, not all the strata reported by the drillers to be impermeable are actually so. For example, zones in a test well on the Hacienda Huancara (well T-1) described as "tight" and "impermeable" in the driller's log proved to be highly permeable.

Structure.—The structural geology of the valley of the Río Elqui is poorly known. Visual evidence of faulting is present along the south wall of the valley above Marquesa, and the intrusion of a terrane of Upper Jurassic or Lower Cretaceous lava flows by extensive masses of Upper Cretaceous granite and granodiorite could hardly be accomplished without faulting on a grand scale.

Flows of the "Formación Porfirítica" are extensively fractured by joints. The light-colored intrusive granitic rocks have been similarly fractured and intruded by dikes of dark-colored rocks.

Whether the valley of the Río Elqui follows an east-west fault-line depression below Vicuña is debatable, but the general trend is directly across the northeasterly alignment of the principal structural trends of the region. A knowledge of the structural geology of the valley might be helpful in determining the thickness of the Quaternary alluvium, in that it might indicate the location of buried waterfalls. However, so little information is now available on the configuration of the buried valley floor that no reliable interpretations with regard to the thickness of alluvium could be made at this time, even with a detailed structural map.

Geologic History.—Since the intrusion of Upper Jurassic or Lower Cretaceous lavas and tuffs of the "Formación Porfirítica" by granitic rocks of Upper Cretaceous age, the region bordering the valley of the Río Elqui appears to have been subject to continuous erosion. Only along the coast and in the

lower valley of the river itself is there evidence of other events since the end of Cretaceous time.

Marine clay, marl, and shells interbedded with fluviatile deposits extend inland a few miles eastward from the Bay of Coquimbo south of La Serena. These have been identified by Taylor (6, p. 14) as Pliocene in age. Their presence indicates that the coastline was subject to a brief encroachment of the sea at that time, but whether through subsidence of the land or rise in sea level is not known.

Since Pliocene time the region has been uplifted several hundred feet, as evidenced by the steplike sequence of coastwise and valley terraces, the highest of which now stands more than 120 m above sea level where it lies nearest the sea. Whether the uplift was continuous (and the terraces were formed at times when deposition kept pace with uplift) or periodic, with long periods of quiescence between uplifts, is not known. During the Pleistocene there could well have been cyclic changes in climate, here as elsewhere, that produced successive interglacial floods of rock debris to form the valley terraces. Valley scour during periods of glaciation and lowered sea level could have entrenched the flood plain of the river in the previously deposited alluvium.

Features of the modern valley indicate that alluviation of the flood plain has been in progress during Recent time. The Río Elqui has been able, during this period, to erode, sort, and spread evenly along its flood plain the rock debris contributed to the valley by rock slides, quebrada-cone encroachment, and erosive action in the upper reaches of the perennial tributaries.

Valley Erosion and Alluviation.—In an area so high and rugged as the Andes Mountains of the "Norte Chico," which rise from the sea to altitudes of 6,000 meters or more in a distance of less than 130 km, it does not seem to the writer reasonable to assume that a rise or fall of sea level within a range of 100 m or so could have any marked effect upon the ability of the perennial streams of the region to erode and transport rock debris, except perhaps in that part of the region within a short distance from the sea. The climatic factors that determine the magnitude and seasonal variation of stream flow are believed to have been a great deal more important. The modern river carries only coarse sand or fine gravel at its average rate of flow. The thundering floods caused by heavy rainstorms fill the valley from wall to wall above Marquesa and sweep everything before them, leaving a leveled, boulder-strewn flood plain in their wake. One such flood in 1943 swept away several thousand eucalyptus trees 9 years old and eroded a thickness of perhaps 2 to 4 m of the underlying valley floor at the Algarrobal dam site.

The hard-rock channel of the lower valley has been drowned by alluvium throughout its length, and the shape of the buried hard-rock floor is not known. It can be inferred, however, from the features of the valley walls and the few drill-hole records available that the channel is a deep and narrow gorge with a bottom profile roughly parallel to, though probably a little steeper and much more irregular than the modern flood plain. It may have been scoured either by ice or by glacial meltwater during the Pleistocene epoch, perhaps in Wisconsin time, the last great period of ice accumulation.

Results of exploratory drilling in the valley show that permeable zones of alluvium at depth are vertically separated by zones of less permeable material. This sequence indicates that there have been distinct changes in the depositional characteristics of the river. The impermeable zones contain considerable clay that would have been winnowed and carried downstream had the river's eroding and transporting capacity been consistently as high as that of today. Perhaps the most logical explanation of this zonation is that of cyclic climatic changes. That climate is subject to cyclic variation is widely accepted. During long dry periods the Río Elqui must have been an ephemeral or sporadic stream, and its power to sort and transport the debris that accumulated in the valley—from the quebrada cones and hillside slides—must not have been sufficient to keep pace with the influx of material. Thus, clayey, rather impermeable colluvium must have choked the valley. The volume of colluvium that entered the valley in any such period probably depended on the intensity and duration of the cycle. As the climate changed, the rate of precipitation and the volume of stream flow increased. Eventually, the stream must have been able, in part, to erode and shift the colluvial deposits, sorting the alluvium and broadening its flood plain, but generally leaving some of the clayey material undisturbed. During "wet" cycles it was able to sort out the fines in the rock debris added to it, and to carry these downstream, leaving the coarse material in place. This process produced permeable zones, examples of which are the modern flood plain alluvium and the buried aquifers in the fill. When the stream could erode and transport all the material entering the flood plain, or more, it began to cut its channel down.

It follows, therefore, that the zones of permeable alluvium vary in thickness, but they must, by virtue of their origin, be more or less continuous along the valley. A thickening of individual zones down valley and a vertical gradation from permeable to semipermeable to impermeable zones might be expected. The modern flood plain deposits are highly permeable throughout the length of the valley. In vertical section the cone deposits of clayey colluvium issuing from the quebrada mouths may be expected to interfinger with the better-sorted valley alluvium. During the dry climatic periods, colluvial cones probably extended entirely across the flood plain. During periods of considerable river flow, quebrada-cone colluvium probably was eroded, sorted, and spread down the flood plain shortly after it encroached upon the valley. In the intermediate climatic stages, as at present, the quebradas restrict or occasionally impound the waters of the river, but lakes thus formed today are short-lived. Sediments deposited in the pools above such natural dams are swept downstream when the dam is breached, and the river reestablishes a smooth gradient in a few years. Quebrada cones, therefore, restrict the river only temporarily in its upper reaches where the canyon is narrow and easily choked by debris. Down valley, the effect of colluvial-cone material on the permeability of the fill is less important because the terrane is less rugged and the formation of such deposits is not favored.

The permeability of the alluvium in certain parts of the valley may be related to the character of the rocks of the valley walls. Quebradas Talca and Las Animas issue from an area of granitic rocks and have cones which are

distinctly permeable. An examination of cut banks along Quebrada Talca shows extensive continuous zones of relatively pure quartz sand that would make an excellent aquifer.

Alluvial terraces are extensively developed along both sides of the flood plain of the Río Elqui. Terraces along the Ríos Claro and Turbio, and possibly as far downstream along the Río Elqui as Puclaro, are considered to be of only local significance. Their origin probably can be attributed to local changes in the base level of the stream, and it is likely that their physical char-

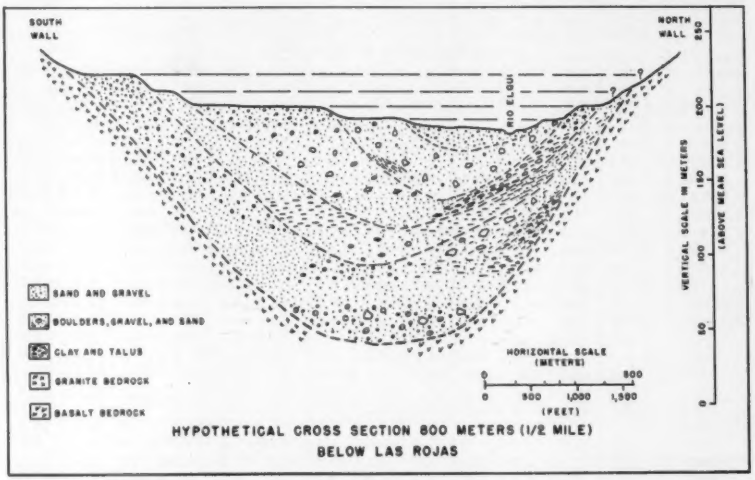


FIG. 10. Hypothetical cross section 800 meters (half a mile) below Las Rojas.

acteristics are similar to those of the material that forms the upper portion of the flood-plain deposits. Between Puclaro and Las Rojas, terraces increase in number and areal extent. These may or may not be of the same sequence of deposition as the terraces farther downstream. Below Las Rojas is a system of 5 well-developed terraces. Figure 10 is a sketch showing a hypothetical north-south cross section across the valley about 800 m below Las Rojas.

The highest terrace surface rises more than 100 m above the flood plain near the mouth of the Río Elqui. Broad coastwise marine terraces merge landward with the alluvial terrace surfaces. The most obvious explanation for these terraces in the lower valley is that they are the result of continental uplift along the coast of Chile. As the coast was uplifted the river cut a trench into its former flood plain, leaving remnants of this flood plain as terraces on one or both sides.

SURFACE WATER.

The water of the Río Elqui is derived almost wholly from melting snow and ice during the summer months, October to April, and from rains in the

foothills and front ranges during the winter months, April to October. Most floods occur in summer, generally in the 4-month period November through February, as a result of rains or unusually rapid thaws in the High Cordilleras.

The Department of Irrigation of the Republic of Chile has gaged the flow of the Río Elqui at two principal stations, Rivadavia and Almendral, since May 1928. The river and staff gage at Almendral are shown in Figure 9. The records of flow past these stations are summarized in Tables 1 and 2.

TABLE 1.

AVERAGE FLOW OF THE RÍO ELQUI AT RIVADAVIA, IN CUBIC METERS PER SECOND, BY MONTHS.[a]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1928	—	—	—	—	12.5	15.7	13.9	12.8	12.6	11.6	20.9	21.5	15.2
1929	19.4	16.7	11.6	9.2	8.3	8.8	10.3	7.2	7.7	8.6	11.3	15.4	11.2
1930	13.7	13.0	10.1	10.1	11.3	10.6	10.6	11.0	21.6	20.5	48.9	56.4	19.8
1931	46.3	37.7	21.6	20.2	18.2	15.9	14.0	12.3	10.8	13.3	11.4	11.3	19.4
1932	10.3	11.8	9.6	10.0	10.2	12.3	11.9	11.6	9.1	9.9	11.7	15.9	11.2
1933	14.1	18.3	15.1	11.6	11.9	11.4	11.9	9.4	8.3	9.9	13.3	11.6	12.2
1934	10.8	11.1	9.3	9.7	14.2	14.1	12.9	11.7	16.0	15.4	31.7	37.9	16.2
1935	33.0	24.0	16.0	14.9	13.0	14.1	10.5	10.5	8.0	6.8	12.3	9.6	14.4
1936	7.9	13.2	9.1	9.3	10.5	9.8	9.6	8.8	6.4	7.4	6.6	6.3	8.7
1937	6.1	6.6	6.2	6.2	6.9	6.2	6.2	4.4	5.1	6.4	9.0	12.4	6.8
1938	10.9	10.0	11.6	9.8	9.4	10.0	8.6	7.2	6.0	7.0	8.1	6.6	8.8
1939	6.3	6.7	5.6	6.5	6.2	5.5	5.1	4.3	4.1	4.9	5.1	5.1	5.5
1940	6.0	6.5	6.1	6.6	6.7	7.8	8.9	9.0	11.0	11.8	20.4	29.5	10.9
1941	28.5	18.5	12.5	13.9	20.2	15.5	13.5	18.0	20.7	41.2	78.0	87.6	30.7
1942	73.8	59.3	33.8	32.4	19.2	16.9	16.0	14.9	24.6	23.3	55.5	64.0	36.1
1943	52.6	42.8	24.5	22.9	18.1	16.0	18.3	11.7	11.5	13.0	16.5	17.1	22.1
1944	18.2	22.6	12.9	12.3	9.2	9.9	10.3	9.0	12.2	14.1	15.4	12.7	13.2
1945	10.7	13.5	11.7	11.0	12.6	10.3	8.9	7.7	7.6	7.3	7.9	6.6	9.7
1946	6.2	6.5	5.2	5.5	5.0	5.5	6.1	5.5	5.2	8.1	7.3	7.6	6.1
1947	7.6	7.4	7.1	6.4	5.3	5.8	5.7	5.2	5.7	6.5	6.3	4.7	6.1
1948	4.0	2.9	3.0	3.2	3.1	3.2	4.0	5.6	5.8	8.8	9.6	10.8	5.3
1949	8.2	8.3	8.5	8.1	—	—	—	—	—	—	—	—	8.3
Monthly average	18.8	17.0	12.0	11.4	11.0	10.7	10.3	9.4	10.5	12.2	19.4	21.5	

[a] Records obtained through the courtesy of the Departamento de Riego, Dirección General de Obras Publicas, Republic of Chile.

During the period from May 1928 through April 1949 the average monthly flow of the Río Elqui at Rivadavia has always exceeded the average monthly flow at Almendral (36 km down valley) during the months of January, February, and March. This probably can be attributed largely to diversions for irrigation between the two stations during the late summer and fall when rainfall almost never occurs in the lower valley. However, ground-water recharge may constitute a part of the loss. Winter rains in the lower valley probably account for the greater flow past Almendral in the months of May through September; and perhaps increased effluent seepage of stored ground water, originating in part as influent seepage on the irrigated lands, provided the excess flow in the summer.

TABLE 2.

AVERAGE FLOW OF THE RÍO ELQUI AT ALMENDRAL, IN CUBIC METERS PER SECOND, BY MONTHS.[a]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1928	—	—	—	—	11.1	18.5[b]	15.7[b]	12.0	8.5	9.6	16.0	15.5	13.4
1929	13.7	12.3	8.7	8.0	7.2	7.9	9.7	6.3	5.3	6.3	8.5	13.1	8.9
1930	11.6	10.9	11.1[b]	11.1[b]	11.9[b]	11.3[b]	12.6[b]	12.6[b]	20.7	19.2	28.2	27.3	15.7
1931	25.6	23.5	20.0	12.2	20.3[b]	18.5[b]	18.4[b]	16.5[b]	15.0[b]	17.0[b]	17.6[b]	15.9[b]	18.4
1932	8.9	8.9	6.5	9.0	9.0	12.4[b]	10.9	9.2	4.9	6.9	10.5	15.1	9.4
1933	11.2	11.9	11.5	10.9	9.5	9.0	9.1	6.7	5.7	6.3	7.9	7.8	9.1
1934	7.2	6.5	6.2	18.5[b]	15.1[b]	15.4[b]	14.2[b]	12.0[b]	11.8	14.6	22.0	21.3	13.9
1935	20.2	17.1	12.6	13.8	11.8	15.3[b]	13.4[b]	10.5	5.5	4.4	9.0	7.0	11.7
1936	5.8	9.0	7.0	7.5	9.2	9.2	8.9	8.1	4.4	4.6	4.6	4.3	6.7
1937	3.7	4.3	4.6	4.6	6.1	5.8	5.9	4.6[b]	4.1	5.2	6.8	10.0	5.5
1938	8.2	6.9	8.8	8.0	8.0	9.3	8.0	6.3	4.4	4.3	5.9	4.4	6.9
1939	4.2	4.5	5.2	4.8	5.8	5.2	5.0	3.9	3.1	3.1	3.6	3.6	4.3
1940	4.3	4.9	4.7	5.3	6.0	7.0	8.4	7.5	7.2	10.3	15.8	18.3	8.3
1941	17.5	14.5	9.5	11.6	21.8[b]	17.9[b]	11.8	24.2[b]	16.2	29.1	35.1	34.0	20.3
1942	34.0	24.6	34.6[b]	20.1	17.3	22.0[b]	22.2[b]	17.1[b]	20.9	19.4	28.0	29.1	24.1
1943	27.1	22.5	24.1	17.7	14.0	17.0[b]	19.0[b]	13.4[b]	9.6	10.3	9.8	11.3	16.3
1944	12.2	17.7	10.5	12.3	11.2[b]	17.0[b]	13.7[b]	11.6[b]	12.3[b]	15.3[b]	17.9[b]	14.5[b]	13.9
1945	10.3	14.7[b]	10.6	11.1[b]	11.4	10.7[b]	9.7[b]	8.9[b]	6.6	6.0	6.1	5.6	9.3
1946	4.7	4.8	4.3	4.1	7.1[b]	7.5[b]	6.6[b]	4.1	3.3	5.5	5.1	4.6	5.1
1947	4.4	5.1	4.6	4.3	3.4	4.2	4.0	3.4	3.2	3.4	3.3	2.8	3.8
1948	2.7	2.4	2.5	2.8	3.0	3.2	4.3[b]	4.3	4.4	6.9	8.1	8.7	4.4
1949	6.7	7.4	6.9	7.4	—	—	—	—	—	—	—	—	2.4
Monthly average	11.6	11.2	10.2	9.8	10.5	11.6	11.0	9.6	8.4	10.0	12.8	13.1	

[a] Records obtained through the courtesy of the Departamento de Riego, Dirección General de Obras Publicas, Republic of Chile.

[b] Months during which the average rate of flow at Almendral exceeded the average rate of flow at Rivadavia.

At the Rivadavia gaging station the largest average flow for a period of 1 month, in 21 years of record, was nearly 87.6 cubic meters (3,090 cubic feet) per second in December 1941. This rate was more than 15 times that for the same month in 1939, and marked the peak of a 2½-year period of high river flow from November 1940 through April 1943. Even during the winter months of those years the average monthly flow was far above the 21-year average, ranging from 13.5 to 32.4 cubic meters (477 to 1,150 cubic feet) per second.

These records (from Table 1) do not reflect the actual severity of the floods. In a few hours the river may become a raging torrent, filling much of the valley above Marquesa from wall to wall and sweeping everything before it. During such torrents the stream may be 6 to 10 m deep, flowing in a stream 500 to 800 m wide, confined within a rock-walled "flume" sloping seaward at a rate of 11 meters per kilometer for a distance of more than 80 km. Four such floods have occurred during the 21-year period 1929–1949.

Diversion of water for irrigation is strictly regulated and the low-water flow is entirely appropriated. In fact, the water security of the irrigated lands is rated by engineers of the Frederick Snare Corp. at only about 65 percent;

that is, an average of one crop in three is lost for lack of water. Records of diversions and stream flow obtained by down-valley traverses indicate that total diversions at any given time during the irrigating season exceed by far the stream flow at any station, pointing to a very large contribution by return flows, both surface and underground.

River water is the source of most rural domestic water supplies in the valley, and it is used without any sanitary precautions. The only industrial use of river water is at the Juan Soldado Cement Plant 8.5 km north of La Serena.

TABLE 3.

CHEMICAL ANALYSES OF WATERS FROM STREAMS IN THE VALLEY OF THE RÍO ELQUI DURING FEB.–MARCH, 1950.*

(Parts per million.)

Sample no.: Date of collection:	1 2/25	2 2/25	3 2/21	4 3/7	5 2/21	6 3/8	7 3/8	8 3/2
Silica (SiO_2)	26	17	22	16	15	16	16	16
Iron (Fe)	7.14	1.40	7.70	5.18	6.30	2.80	3.92	4.48
Calcium (Ca)	64	48	61	63	74	74	132	119
Magnesium (Mg)	10	6.6	10	9.1	11	11	25	63
Sodium (Na)								
Potassium (K)	52	23	32	47	44	49	108	412
Bicarbonate (HCO_3)	117	132	124	140	166	175	272	370
Sulfate (SO_4)	137	38	115	119	130	131	207	396
Chloride (Cl)	30	12	21	32	28	32	144	469
Nitrate (NO_3)	33	21	—	—	—	—	3.2	48
Total hardness as $CaCO_3$	203	146	194	193	228	232	431	323

* Analyses made by the chief chemist, Juan Soldado Cement Plant, La Serena, Chile.

Sample: 1 Río Turbio above Algarrobal; 2 Río Claro above Algarrobal; 3 Río Elqui at Algarrobal; 4 Río Elqui at Algarrobal; 5 Río Elqui at Almendral; 6 Río Elqui at Almendral; 7 Río Elqui at Islón; 8 Quebrada Santa Gracia near mouth.

A small hydroelectric plant using return flows from irrigated terrace lands is in operation across the valley from Altovalsol.

Quality of Surface Water.—The water in the Río Elqui is excellent for irrigation, although it is too hard and contains too much iron to be ideal for domestic or public supply. An increase in the dissolved solids down valley is noted from the analyses (Table 3) of samples collected from the river during the late summer of 1950, after the irrigation season was several months along. This increase could be expected because the total diversion exceeds the average rate of river flow during the irrigating season; thus, much of the river flow in the down-valley section is return flow from irrigated lands, where evaporation and transpiration have concentrated the salts in the water.

The quality of water in Quebrada Santa Gracia, as shown by the analysis in Table 3, indicates the effect of irrigation use upon the quality of water. Quebrada Santa Gracia is flanked by alluvial terraces ideal for cultivation. Precipitation in its drainage area is far too little to provide irrigation water for the lands, or even to cause perennial flow in its channel. Canals tapping

the Río Elqui several kilometers up valley from the mouth of Quebrada Santa Gracia cling to the steep northern wall and pass through several tunnels high above the flood plain, before leading into the quebrada. These canals eventually spill water onto the terrace lands far up the quebrada. The summer and fall flow of the stream itself is probably derived almost wholly from return flows from the irrigated lands, either above-ground or underground.

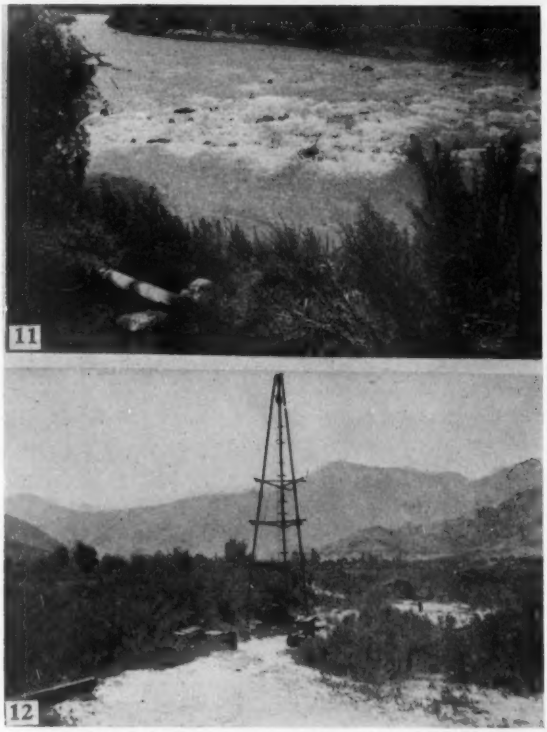


FIG. 11. The Río Elqui near the mouth of Canal Cutín, northeast of well T–3, near Pelicana. Milky appearance attributed to "rock flour."
FIG. 12. View eastward from well T-1 at Huancara showing well T-1-A, 30 m deep.

It is interesting to note that, after several hundreds if not thousands of years of irrigation along this quebrada, the chemical quality of return flow in Quebrada Santa Gracia is such that it is usable on many types of crops. This indicates especially good soil drainage, in that the permeable subsoil is capable of draining the relatively saline waters away from the soil surface almost as rapidly as they are concentrated by the processes of evaporation and transpira-

tion. Precipitation of salts at places in the flood plain where return flow is pooled in low spots and evaporated provides an appearance of snow.

There is a seasonal variation in the quality of the water of the Río Elqui, as might be expected. According to the records of the chief chemist of the Juan Soldado Cement Plant which obtains water from the river through a diversion at Islón, the dissolved solids in winter amount to less than half the dissolved solids in summer. This is probably because the river flow in winter is greater and there is little or no irrigation use.

The physical character of the river water also changes with the seasons. In summer the water is turbid, almost milky (Fig. 11); this is attributed to suspended "rock flour" derived from the melting ice of the mountain glaciers in the headwaters of the drainage basin. In the winter the water is clear except during the floods, being derived from rainfall in the front slopes and foothills.

Throughout the year water in the extreme lower stretch of the river is generally crystal clear. This is attributed by the writer to a natural filtering of the water, as it is believed that most if not all of the low-water flow in the stream has moved underground at least a short distance in its passage to the sea. Large increments in river flow in the lower valley that cannot be traced to surface sources are noted from gaging-station records. The writer has examined numerous springs in the valley floor flowing 50 to 80 liters per second (about 800 to 1,200 gallons of water a minute) from coarse alluvial sands and gravels. There is good reason to believe that in many other places effluent ground water contributes directly though invisibly to the channel of the stream.

GROUND WATER.

General Relations.

Ground-water supplies in the valley of the Río Elqui are obtained exclusively from the alluvium that underlies the terrace lands and the valley floor. The bedrock of the valley includes no formations that are known to be good aquifers, but there may be undiscovered water supplies in the consolidated rocks.

Alluvium in the form of cones and talus slopes blankets the valley margins and extends hundreds of feet above the valley floor. Although this alluvium includes small bodies of water-sorted materials and receives precipitation during the winter months, it does not constitute a dependable source of water supply, not only because for the most part it consists of poorly sorted materials, but also because it is so well drained. Verbal reports of difficulties with a well dug on the Vicuña cone emphasize the importance of cone drainage and the erratic occurrence of permeable zones. The well penetrated little permeable material and it goes dry in the summer. The depth of the well is not known.

Alluvium forming the terraces that flank the lower valley includes well-sorted zones having the characteristics of a good aquifer, overlain and underlain by poorly sorted alluvium that appears to be of low permeability. The

ground water in the terrace alluvium is largely derived from seepage from its irrigated surface. The water table in the terrace lands, which comprise most of the agricultural land in the valley, may be 30 m or more below the surface. Nevertheless, the deposits where saturated appear generally suited for well development.

The alluvium of the modern flood plain and that of previous cycles of deposition beneath it include the principal aquifers of the valley. The permeability of several zones within the alluvium ranges from low to very high, and the presence of aquifers suitable for development by means of large-capacity irrigation wells has been proved. The bedrock floor has not yet been reached by the drill, although one hole 140 m deep has been drilled.

The primary part played by the consolidated rocks of the valley, so far as ground-water resources are concerned, is to determine the shape and size of the aquifers that occur in the valley alluvium, the "fill." From the evidence available, the scour channel cut into the consolidated rocks must form a steep-walled canyon. There are, no doubt, buried rock narrows and waterfalls at the base of the channel, and these will play an important part in the ultimate development of ground water in the valley. They will be found not only to affect the rate of underflow of water in the "fill," but also to affect the volume of water in storage in certain channel sections by controlling the cross-sectional area of permeable, porous alluvium.

Water in the Valley Fill.

At some depth beneath the land surface nearly everywhere the rocks contain gravity water in their interstices, the pore spaces or fracture openings. Dr. Oscar E. Meinzer's definition (5, p. 27) of gravity water is:

> The gravity ground water of a body of rock or soil in the zone of saturation is the water that would be withdrawn from the body by the direct action of gravity if the zone of saturation and the capillary fringe were moved downward through the body until both were entirely below it and remained in that position a specified period, no water being received by the body and none lost by it except through the pull of gravity.

Within the zone of saturation water is under either hydrostatic or artesian pressure.

In the alluvium that underlies the flood plain of the Río Elqui ground water occurs under water-table conditions in the near-surface deposits and under artesian or semiartesian conditions in the deeply buried deposits.

The thickness of the water-table aquifer is reported to be about 7 m at Rivadavia and about 20 m at Huancara, some 20 km down valley. Although the drilling records may not be entirely reliable, and considerable variation in the thickness may be expected both along and across the valley, it seems reasonable to expect that the aquifer thickens down the valley.

The water table is never more than a few meters below the flood plain, and often reaches the surface, where water emerges in the form of springs. Much of the water that reaches the Bay of Coquimbo has been alternately surface water and ground water several times in its passage down valley. The water

table nearly parallels the valley floor and has a smooth seaward gradient of about 11 meters per kilometer.

Beneath the water-table alluvium are successive zones several meters to tens of meters in thickness, ranging from nearly impermeable to highly permeable; the water in the permeable zones is under artesian pressure. Though available drilling records are largely unreliable in showing the permeability of the different strata of alluvium penetrated, measurements of the cumulative specific capacity (Fig. 18) and of the static water level in the well at Huancara (T-1) from the base of the well upward warrant the following statement: Deposits at Huancara between depths of 95 and 140 m, the maximum depth reached anywhere in the valley to date, appear to be of low permeability; those between depths of about 35 and 95 m are of high permeability; and those between depths of about 20 and 35 m are of low permeability.

That the water-table alluvium has no local hydraulic interconnection with the zone between depths of 35 to 95 m at Huancara is indicated by the difference of about 0.8 m in the hydrostatic head in the two zones, and by the fact that pumping from the lower aquifer produced no measurable effect on water levels in wells tapping the water-table alluvium in the immediate vicinity of the pumped well.

Whether or not the two aquifers are effectively separated by impermeable alluvium up valley or down valley from Huancara is not known, but it is reasonable to expect down-valley continuity of the permeable artesian zones, for the same reason that the water-table aquifer is continuous and consistently permeable down valley. The artesian aquifer should extend across the valley in the same manner as the modern flood-plain alluvium. Burial by impermeable or less permeable alluvium makes this aquifer no less permeable, and the continuity of the conduit thus formed is not destroyed even by rapid encroachment of quebrada-cone materials. Because of its continuity and high transmissibility and of the steep hydraulic gradient, the alluvium undoubtedly is able to transmit a considerable underflow.

There is a possibility that an aquifer not yet penetrated by any of the exploratory holes may lie at the base of the alluvium in the deepest part of the scour trench. This aquifer, if present, may be the most permeable one in the alluvium, for its deposition would have been accomplished by a swift-flowing stream that had been able to scour bedrock shortly before and that would have had ample power to remove fine-grained materials and to leave behind only coarse, permeable gravel. Such an aquifer might contain water under sufficient artesian pressure to cause wells tapping it in the flood plain below Las Rojas to flow at the land surface. The factors favoring this are (1) the high altitude of the intake area, (2) the presence of an overlying confining bed, in the form of irregular zones of alluvium of low permeability, and (3) the possibility that the aquifer might interfinger with marine clays near the sea, resulting in a partial dam to underflow.

The water table or the artesian-pressure surface of an aquifer can be mapped by referring to a common datum the static water levels or artesian pressures of wells that tap it. The position and shape of the contours on such a map are very significant, for they show not only the source area of the gravity

water but also the direction of movement, the hydraulic gradient, and the areas of natural discharge—if there are any within the area mapped. Such a map is called a piezometric map, and a comprehensive study of ground-water conditions in any aquifer is not complete without a map of this type. Detailed studies may require the preparation of piezometric maps seasonally, based upon water-level measurements in many wells made in as brief a period as possible.

Fluctuation of Ground-Water Level.

Fluctuations of water levels in wells that tap an aquifer may occur as a result of pumping from wells, seasonal variations in the rate of natural recharge or discharge, changes in the rate of evaporation from the aquifer or the transpiration of plants whose roots tap the aquifer, barometric-pressure changes, loading effects (tides, trains passing nearby, etc.), and various other causes. Cyclic fluctuations due to one or more of these causes may range in length from part of a day to several years.

No usable records of water-level fluctuations in wells in the valley of the Río Elqui are available for the period prior to the beginning of intensive studies by the Frederick Snare Corp. In fact, wells in the valley are very scarce. Exploratory holes drilled at the site of the proposed dam at Algarrobal were cased with concrete pipe, and observations of water-level fluctuations in them were begun February 4, 1950.

Periodic measurements of water levels in 64 observation wells in the valley have been made since December 17, 1949. Most of these wells tap the shallow alluvium and were dug for the purpose of water-level observation. Several are grouped in the vicinities of the three areas of intensive study, at Huancara near well T-1, at Puclaro near well T-2, and at La Calera near well T-3. The locations of 52 observation wells, 5 supply wells, and 3 test wells are on record. Hydrographs showing fluctuations of water levels in 13 observation wells and 3 supply wells are shown on Figure 13, and water-level records for the same wells are on record.

Most of the observation wells are uncased if shallow, or shored with timbers if deep. Some are cased with concrete tile.

Because none of the wells were equipped with automatic water-level recorders it is not possible to make a detailed analysis of the short-term records. Most of the wells were measured at intervals of a few days or a week, but hourly measurements were made on the wells at the site of the pumping test on Huancara Well T-1 (Fig. 12).

No records are available for periods longer than 5 months on individual wells, but these records do indicate the magnitude of the late-summer water-level fluctuations. The records seldom show a range of more than 0.8 meter for the 5-month period. Only two observation wells, both in the vicinity of Diaguitas, about 8 km east of Vicuña, and one supply well (S-3) showed a total range of fluctuation in excess of 1 m. Available records indicate that there are large fluctuations in water level only in wells on the terrace lands.

Records of water levels in wells were obtained to determine, so far as possible, (1) the degree of hydraulic interconnection between the shallow aquifer

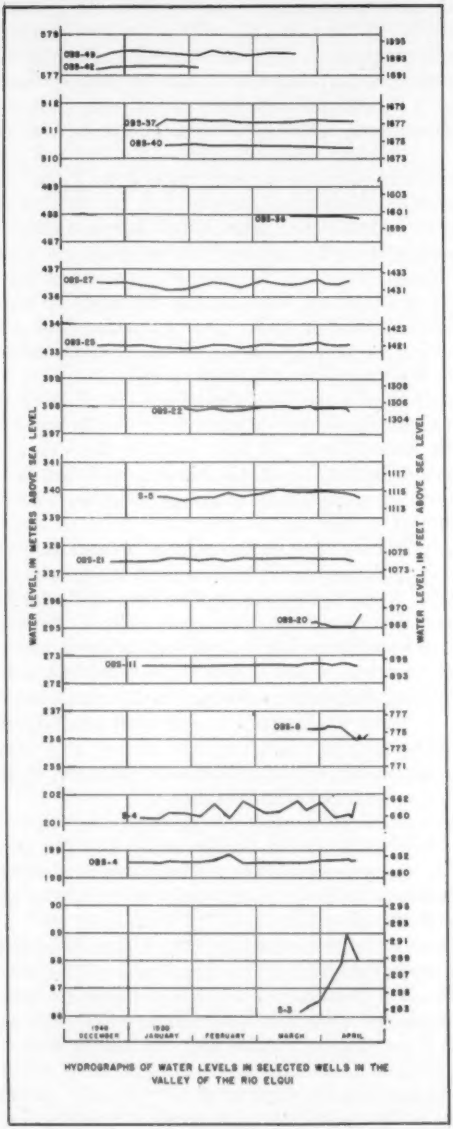


FIG. 13. Hydrographs of water levels in selected wells in the valley.

and the deeper aquifers at the pumping-test sites, (2) the "normal" range of fluctuation of the water table in the shallow alluvium and the relation of water level to river stage, (3) the direction and rate of slope of the water table in the flood plain and beneath the low flanking terraces, and (4) the relation between the water table and such surface features as springs, vegetation in or along the margin of the flood plain, and gains or losses in river flow through selected reaches of the stream. However, the more complex of the above objectives were found to be unattainable through use of the available records.

Had pumping tests been made in the water-table alluvium it would have been possible to use records of water-level fluctuation in wells near the pumped wells to calculate the hydraulic characteristics of the water-table aquifer.

The hydrographs on Figure 13 show the characteristic water-level changes in selected wells during the period of available record. None of the fluctuations can be attributed to effects of pumping from wells. Most of them are probably the results of changes in the rate of flow of the river (e.g., in wells obs-11, 21, 22, 36, 37, and 40), or of changes in the amount of flow diverted for irrigation up valley from the well (e.g., in wells S-3, S-4, obs-8, 20, S-5, obs-42, and 49). Some of the records may reflect the effects of changes in the transpiration rates of plants in the flood plain (e.g., in wells obs-4, 25, and 27).

Although no map of the water table has been prepared, the records have been referred to mean-sea-level datum. In some reaches of the flood plain the water table is above and slopes toward the river; in other reaches it is below and slopes away from the river. The dominant feature is, of course, the down-valley slope of the water table, which in general nearly parallels the average slope of the flood plain.

Sources of the Ground Water.

The principal source of ground water in the valley of the Río Elqui is the Río Elqui itself. The winter storms provide some water to the tributary areas in the form of rain or snow, and it is likely that much of this seeps into the surficial materials of the quebradas and ultimately reaches the main valley to contribute to the underflow in the valley alluvium.

Numerous intermittent streams are present in the quebradas of the Elqui Basin. Springs flowing 2 or more liters a second rise in each large quebrada where its floor is on or near the consolidated rock, and the flow disappears down slope where the alluvium thickens. In most instances this water never reappears in the lower part of the quebrada, and if it enters the main valley at all it must do so underground.

The valley walls and tributary quebradas are generally mantled by rock debris. In many places this pervious mantle serves as a reservoir for water derived from snow melt or rainfall; because it is generally continuous with the valley alluvium, its ground waters move down slope to join the body of ground water beneath the flood plain, often without ever reappearing at the surface.

It is apparent that the river actively recharges the water-table aquifer in some reaches and receives effluent ground water in others. There probably

are times during which the seepage is influent throughout the lower valley (during floods) and times during which it is effluent throughout (during prolonged drought).

There is evidence in the form of springs (Figs. 14, 15) that significant amounts of water applied to the irrigated terrace lands seep underground and

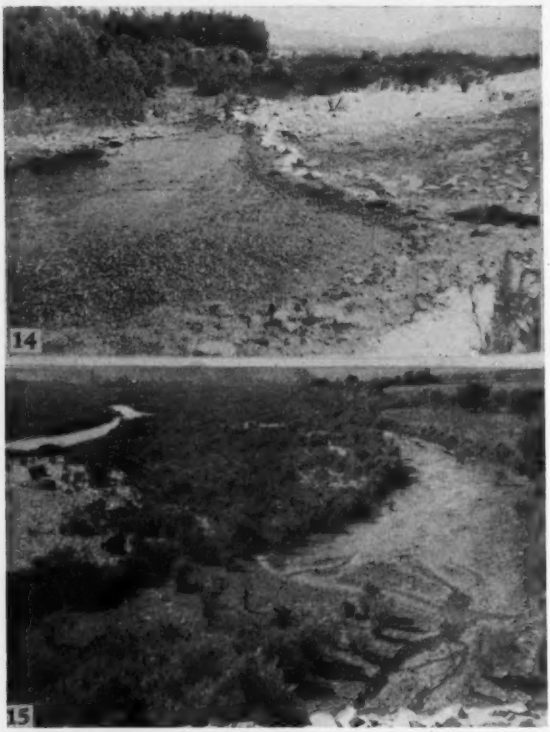


FIG. 14. Vertiente Saturno, a large spring on the south margin of the flood plain west of observation well 10, near Quebrada Talca (flow is 1100 gals. per min.).

FIG. 15. Small spring west of Almendral, eastward from south wall.

return to the river or contribute to the underflow in the water-table alluvium. Marshy areas are not uncommon, and significant increases in the acreage of arable land could be made by proper drainage. The water from springs is carefully segregated from river water, the diversion of which is strictly regulated (Fig. 16).

Movement of the Ground Water.

A part of the water derived from melting snow and rain on the talus slopes that flank the valley and the tributary quebradas seeps into the loose rock and percolates downward to the zone of saturation. Thence it moves down gradient to join the body of ground water beneath the flood plain and terrace lands. In its course down the alluvium-choked quebradas, a part of it in places appears at the surface, forming springs, where a rock ledge or other impermeable deposit bars or restricts its movement underground. Once across the barrier it seeps back into the alluvium and continues valley-ward, to join the "trunk" aquifer of the valley near the quebrada mouth.

FIG. 16. Discharge from the springs, south of Marquesa, crossing a river-diversion canal.

Far up the Ríos Claro and Turbio the hard-rock floor of the valley passes beneath a mantle of loose rock and sand that the rivers have not been able to transport down the valley. The unconsolidated alluvium of the flood plain fills a scour trench and is saturated about to river level throughout the length of the valley. The water within it flows down the valley with about the same hydraulic gradient as that of the river itself.

Most of the ground water beneath the flood plain is probably derived from the river, and in its course along the valley a free exchange of water occurs. Where the buried scour trench broadens and deepens, and the alluvium comprising the aquifer is able to transmit more water than in the section immediately up valley, under the same hydraulic gradient, the river loses water to the aquifer. Where the buried trench constricts, or the alluvium is less perme-

able, the aquifer is less able to transmit water; the hydraulic gradient in it flattens and water emerges from the flood plain. This occurs either as effluent seepage directly into the river, or as springs in the flood plain that form brooks. These little streams course their way down the valley, in places disappearing through seepage loss, in other places joining the river, or being diverted for irrigation.

Ground water that originates as seepage loss on the irrigated lands percolates downward to the water table and moves down gradient, which is generally in the direction of the Río Elqui. Some of the ground water derived from seepage loss on the terrace lands emerges in springs that are common along the bases of terrace escarpments. Most of it, however, joins the principal body of ground water in the alluvium beneath the flood plain and continues its course down valley. This is true except where the terrace lands flank the low coastwise plain along the Bay of Coquimbo. There, spring flow resulting from effluent ground-water seepage, and underground flow as well, wastes itself in a coastal marshland.

Seepage losses in the northern end of the Lagunillas Basin, which is irrigated by water from the Río Elqui, contribute to the body of ground water in the alluvium of the Basin. Quebrada Lagunillas, which drains westward into Guanaqueros Bay, is fed by springs that derive at least a part of their flow from these seepage losses. A ground-water divide lies somewhere between Quebrada Lagunillas and the southern margin of the valley of the Río Elqui. Except for evaporation and the transpiration of plants in the valley, this is the only known loss of water from the drainage basin of the Río Elqui.

Because of vertical variations in the structure and texture of the alluvial deposits that fill the scour trench of the Río Elqui, one or more aquifers in the alluvium contain confined water. The confined water is free to move down valley only, and where confined takes no part in the free exchange of water between the river and the water-table alluvium. If no avenue of escape exists by which this water can reach the land surface in the valley it must discharge into the Bay of Coquimbo from submarine springs.

The body of water in the water-table aquifer moves seaward, and at the valley mouth it spreads fanwise beneath the coastal marshland. As it approaches the Bay of Coquimbo it rises toward the land surface, being forced upward by a wedge of salty water from the bay. Finally it forms a broad, shallow zone of fresh-water seeps, or springs, and mixes with the waters of the bay.

Chemical Constituents of the Ground Water.

Although the only analyses of ground waters in the valley available are for samples obtained from the well at Huancara (T-1) during two different tests, ground waters are reported by chemists at La Serena to be universally hard and rather high in sulfate content, and often to contain sufficient iron in solution to stain clothes and plumbing fixtures. From the standpoint of irrigation use the water is generally good, and diversions from many springs in the valley for this purpose are recorded. The results of analyses given in the table below indicate the chemical quality of the water.

It is likely that ground waters originating as return flows from the irrigated lands contain larger and perhaps damaging quantities of dissolved salts, but no records are available for such waters.

TABLE 5.

CHEMICAL ANALYSES OF WATER FROM THE HUANCARA WELL (T-1).

(Parts per million.)

Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Total hardness as ($CaCO_3$)
(1) 14	3.5	78	11	32	217	89	24	—	238
(2) 17	1.7	81	12	33	219	102	21	2.6	251

(1) Date of collection: Feb. 21, 1950. Well screened from 75 to 94 meters (246–308 ft).
(2) Date of collection: Mar. 15, 1950. Well screened from 65 to 94 meters (213–308 ft).

Ground-Water Developments.

At present only small withdrawals of ground water are made from wells and galleries in the valley. A single gallery supplies the cities of La Serena and Coquimbo, and a single well meets the requirements of the Juan Soldado Cement Plant near La Serena during very dry summers. No more than 10 dug wells have been put down in the valley, and no drilled tubular wells were in use prior to 1950. Ground-water supplies derived from perennial springs are diverted for irrigation purposes in several places, but it is likely that most spring flow enters the river directly.

Supply Wells and Galleries.—A tubular public-supply well drilled in December 1949 at La Serena, producing through open-end, 12-inch pipe set to a depth of 63.5 m, was pumped at rates up to about 28 liters per second, with a drawdown of about 35 m at that rate. When this well is completed with slotted pipe or screen it is expected that the specific capacity will be much increased.

A buried horizontal gallery about 16 km east of La Serena and about 300 m east of the intake of the Floto Canal yields about 90 liters per second and provides the public water supply of La Serena and Coquimbo by gravity flow. It consists of a conduit made of perforated concrete slabs and has a cross section of 1.3 m by 0.6 m. The gallery lies about 6 m below the flood plain level and extends transversely across the valley a distance of 328 m. The supply is almost constant, and no significant seasonal fluctuation of the water level is apparent.

The Juan Soldado Cement Plant has a buried horizontal gallery about 70 m south of the railroad and about 10 m east of the Juan Soldado Canal. It yielded about 250 liters a second with only 1.33 m of drawdown when tested on January 28, 1950. This gallery consists of two round concrete tubes having an inside diameter of 0.5 m lying side by side in a gravel-filled trench. The tubes have openings in their upper circumference and feed into a circular pit 2 m in diameter and about 7 m deep. No significant fluctuation of static water level in the pit is reported, and nearby springs apparently are not affected by prolonged pumping from the gallery.

Domestic, stock, and railroad supplies are obtained from shallow dug wells which extend a few feet below the water table. The number of these wells is few and the withdrawal of water from them is insignificant.

Springs.—Perennial springs with moderate to large rates of discharge occur at intervals in the flood plain of the river. One spring, about 300 m northwest of the Huancara test well (T-1) near Vicuña, flows an estimated 75 liters per second. Another spring about 500 m south of Marquesa flows an estimated 35 liters per second. Neither of these springs can be attributed to water losses from canals because no canals are nearby. Both springs rise at the valley margin at slight declivities in the land surface and flow down the valley to join the river. Past efforts to divert the flow for irrigation are evident. Near the southern margin of the valley above Las Rojas, two canals, Vertiente

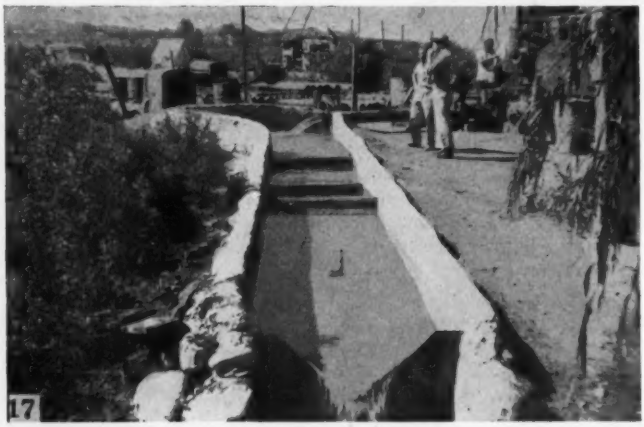


FIG. 17. Test well T-1 near Vicuña, the first drilled tubular well.

Saturno nos. 1 (Fig. 14) and 2, obtain their supply exclusively from spring flow. A part of the water may be derived as return flow underground from irrigated lands nearby at the southern valley margin, but the major part is believed to represent natural effluent seepage in the floors of abandoned channels of the Río Elqui at this point. Vertiente Saturno no. 1 was flowing at least 70 liters per second when the area was visited on March 30, 1950. Numerous small unused springs have been noted in the valley. They give evidence of the common availability of ground water at shallow depth.

Test Wells.—Three test wells were being drilled in the valley at the time of the writer's visit. One (T-1) has been perforated between depths of 30 and 94 m and test-pumped. Drilling records for the other two wells, one (T-2) at Puclaro and the other (T-3) at La Calera, show a series of permeable zones separated by semi-permeable to impermeable zones. Both these wells have reached depths in excess of 50 m.

At Huancara, about 1.5 km down valley from Vicuña, a test well (T-1, Fig. 17) was drilled to a depth of 140 m without penetrating bedrock. Because the alluvium below a depth of 94 m appeared, from the cuttings and drilling records, to be unsuitable for development as a source of ground-water supply, the hole was plugged back to that depth with gravel. The well was cased with 12-inch casing from the surface to a depth of 30 m and with 10-inch from the surface to 91 m. Torch-slotted 8-inch casing was set from 91 to 94 m.

To observe the effects upon the water-table of pumping from the well, a number of pits from 2 to 3 m in depth were dug in the vicinity of the well. The water table here is at a depth of approximately 2 m below the land surface. An observation well (T-1-A) 30 m deep was drilled at a distance of 50 m up valley from the pumped well.

Hydraulic Characteristics of the Aquifers.

The hydraulic characteristics of an aquifer that determine its ability to provide a sustained ground-water supply are its coefficients of transmissibility and storage. Transmissibility (7, p 520; 8, p 11) has been defined as the rate of flow, in gallons a day, through a cross section of the aquifer 1 mile wide and the full saturated thickness of the aquifer under a hydraulic gradient of 1 foot per mile. This is equivalent to a rate of flow in gallons a day through a vertical cross section of the aquifer 1 foot in width and of a height equal to the saturated thickness of the aquifer under a hydraulic gradient of 100 percent (1 foot per foot).

The storage coefficient has been defined as the amount of water, expressed as a fraction of a cubic foot, derived from a vertical prism of the aquifer having a cross-sectional area of 1 square foot and a height equal to the saturated thickness of the aquifer by lowering the water level 1 foot. Under water-table conditions the storage coefficient is essentially the same as the specific yield. By definition, the specific yield (5, p 28) of a rock is the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume. Specific yield may be expressed as a percentage.

Because the basic equations for the determination of the transmissibility and storage coefficients assume a widespread, uniform aquifer, the shape and heterogeneous character of the alluvium in the Elqui Valley make accurate and reliable calculation of its hydraulic characteristics difficult. Data are available for a series of six pumping tests made with a single well (T-1) at Huancara, the results of which indicate that, between depths of 30 and 94 m at this location, there is an aquifer or zone of aquifers having a very high coefficient of transmissibility.

In the series, successively greater lengths of the casing in the well were perforated, beginning with the interval between 91 and 94 m and working upward in the well. After each test the perforating knives were run into the well, and an additional length of casing was perforated. A surge block was used to develop the zone of alluvium opposite the new perforations, and the test pump (a deep-well turbine) was reset and pumping resumed (Fig. 18).

Conditions of the test were carefully controlled and complete records were tabulated. Simultaneous measurements of discharge were made using a 6-inch

orifice and manometer, and a 90° V-notch weir. Nonpumping water levels were measured with a steel tape and checked with the electrical-contact method and an air-line gage. Pumping water levels were measured using the electrical-contact method and the air line. Discharge rates were regulated by opening or closing a valve, and were kept essentially constant by close control of motor

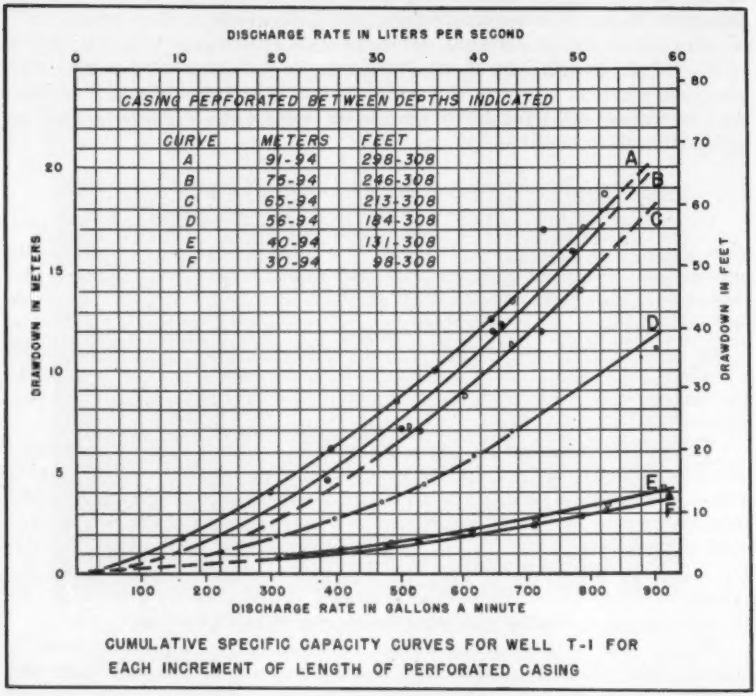


FIG. 18. Cumulative specific-capacity curves for well T-1 for each increment of length of perforated casing.

speed. A tachometer was read at short time intervals to enable accurate throttle control. The well is in the approximate center of the valley, some 340 m from the river.

Although one nearby well (T-1-A) is 30 m deep, neither it nor any of the dug observation wells showed any water-level decline that can be attributed to the withdrawal from the pumped well. This demonstrates the lack of local hydrostatic continuity between the water-table aquifer and the aquifer tapped by well T-1 between depths of 30 and 94 m. It also prevents calculation, with the data obtained, of the storage coefficient of the aquifer tapped by well T-1.

The transmissibility of the zone tapped by the well has been calculated by

the Theis recovery method (8, p 94). It is evident from these calculations that the most permeable zone of the alluvium is between depths of 40 and 65 m (note in Fig. 18 the large increases in specific capacity when the intervals between 40 and 56, and 56 and 65 m were perforated).

The transmissibility of the alluvium tapped by well T-1 between depths of 30 and 94 m was determined from the recovery rate of water level in the well following a period of continuous pumping for 29⅔ hours (Fig. 19). The well was pumped at different rates between 21.8 and 58.5 liters per second for the

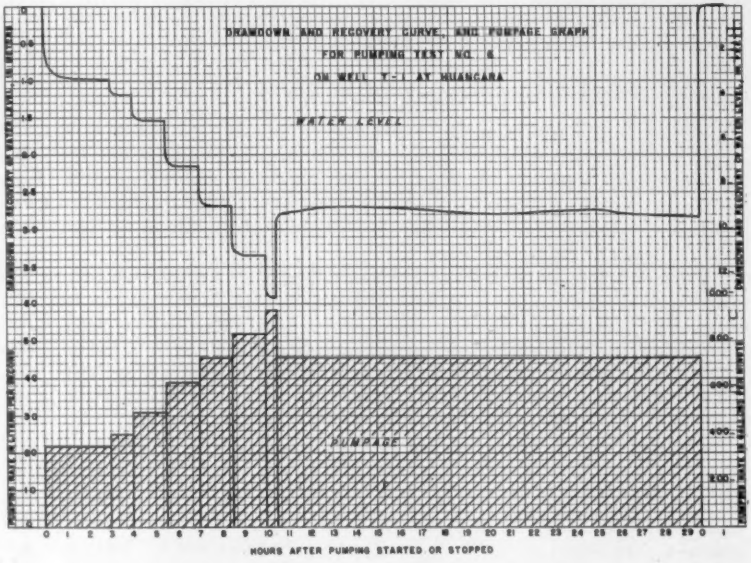

DRAWDOWN AND RECOVERY CURVE, AND PUMPAGE GRAPH
FOR PUMPING TEST NO. 6
ON WELL T-1 AT HUANCARA
WATER LEVEL
PUMPAGE
HOURS AFTER PUMPING STARTED OR STOPPED

FIG. 19. Drawdown and recovery curve, and pumpage graph for pumping test no. 6 on well T-1 at Huancara.

first 10½ hours, and at a rather steady rate of 45.8 liters per second for the last 19⅙ hours. The total pumpage during the 29⅔ hours was about 4,425,000 liters (1,169,000 gallons), and the average rate of withdrawal was about 41.4 liters per second. Adequate data are not available for correcting the basic assumptions of the Theis equation for boundary effects, partial penetration, etc., so that a completely reliable value of the coefficient of transmissibility could not be obtained. The first part of the recovery curve indicates a value of about 750,000 gallons per day per foot, a high value which shows that the alluvium is very permeable. Until better data become available, the figure of 750,000 can be used, with caution, as an approximation.

Well Characteristics.

The specific capacity (the yield per unit of drawdown of water level) of well T-1 under the conditions of the test described above was about 14.9 liters per second per meter of drawdown at a discharge rate of 58.5 liters per second. The graphs on Figure 18 show the variation in the specific capacity of the well with pumping rate and screen opening.

The specific capacity of well S-2 near Islón, which is a horizontal drain, was 188 liters per second per meter of drawdown when tested at a pumping rate of about 250 liters per second.

Most of the dug wells could not be bailed dry after they had reached a depth of about half a meter below the water table.

Possibilities for Future Ground-Water Development.

Although quantitative studies in the valley of the Río Elqui should be made before extensive development of the almost untouched ground-water resources is undertaken, there are excellent possibilities for such development. Economic use of available supplies would require prevention of nonbeneficial natural losses, whether they result from evaporation, transpiration, or underflow into the Bay of Coquimbo.

Evaporation from the soil and transpiration from worthless plants in the marshy areas, or areas in which the water table is close to the land surface, can be reduced by lowering the water table, using a network of shallow wells. The water they produce can be added to the irrigation canals. Permanent destruction of the phreatophytes that blanket the flood plain (Figs. 4, 11, 15) alone would save vast quantities of water, as would a similar practice in the Safford Valley, Ariz. (4).

Underflow of fresh ground water into the sea cannot be prevented entirely, because some underflow must be maintained in order to hold back salt water. However, a large part of the underflow could be diverted into a system of irrigation canals and used on lands that now are desert. Diversion of underflow can be accomplished by wells or perhaps by subsurface dams. Detailed geologic and hydrologic studies will be necessary before the proper method can be determined.

The rate of underflow in the alluvial fill cannot be reliably estimated at this time. The total thickness of the permeable alluvium and the shape of a buried channel cross section are not known for even a single section. The transmissibility of one zone of the alluvium, as indicated by the results of tests on well T-1 near Vicuña, is very large; and the high yield of springs in the water-table alluvium indicates that it, also, is an excellent aquifer. Under the known conditions at the site of well T-1 (width of about 2,600 feet, transmissibility of at least 700,000 gallons per day per foot, and a gradient of about 60 feet per mile) there must be an underflow of no less than 1 cubic meter per second (about 16,000 gallons a minute), and there may be several times this much.

Withdrawals from storage in the aquifer can provide very large ground-water supplies, possibly only with some reduction in stream flow. The maximum development of water resources in the valley will require integrated use

of surface and ground water, which in turn will require detailed studies of the hydraulic relationship between the aquifers and the river before extensive development of underground supplies begins.

Development of ground-water supplies is favored by conditions in the upper valley of the Río Elqui where there are a number of choice sites for hydroelectric plants. The power potentialities far exceed the requirements for the most difficult pumping lifts that might be expected in wells.

CONCLUSIONS.

The rate of precipitation in the drainage basin of the Río Elqui is sufficient to provide water supplies far greater than those now developed. Winter flow and flood waters of the river might be impounded by large dams if such structures were feasible. As they are not, because of the great thickness and high permeability of the valley alluvium (the fill), the only alternative is to develop the ground-water resources in a manner that will effectively increase the total water supply during the irrigating season and result in a diversion of winter flow and flood waters of the river underground.

Results of test drilling and hydraulic tests—and the abundant evidence of the availability of ground water from dug wells and springs in the valley—indicate that large supplemental irrigation-water supplies can be developed without noticeably affecting river flow. Quality-of-water records indicate that the ground water is suitable for irrigation of the crops grown in the valley.

Intensive study of the geology and hydrology of the valley fill, and a scientific integrated development of the total water supply of the valley, surface and underground, based upon results of such study, would greatly increase and perhaps even double the available water supply of the valley. Under the most adverse conditions the use of ground water can be expected to raise the water security in the valley from 65 to 100 per cent.

The promise that ground water holds for the valley of the Río Elqui is very great.

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WASHINGTON, D. C.,
May 1, 1953.

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POLARIZATION FIGURES AND ROTATION PROPERTIES AS APPLIED TO THE IDENTIFICATION OF SOME COBALT NICKEL SULFARSENIDES AND RELATED MINERALS.

RICHARD W. HUTCHINSON.

ABSTRACT.

This paper discusses the applicability of polarization figures and rotation properties to the identification of the sulfarsenides of cobalt, nickel and iron in polished surfaces. The rotation properties of these minerals have been determined and are summarized here. These properties offer a valuable new aid to the identification of the anisotropic sulfarsenides of cobalt, nickel and iron. They do not assist materially in the identification of the isotropic minerals investigated. Oil immersion techniques are not of great value in facilitating identification, but a special application of immersion methods is suggested by studies of the safflorite-löllingite series.

INTRODUCTION.

THE sulfides, sulfarsenides and related ore minerals of nickel, cobalt and iron found in the Cobalt district of Ontario have received much attention from ore microscopists, but certain of these minerals have proved difficult to distinguish by standard microscopic and microchemical methods. The orthorhombic diarsenides described by Holmes (5),[1] and Peacock (8), (9), and the isometric arsenides and sulfarsenides have been the most troublesome, and in the past X-ray studies have been required for their positive identification.

Studies by Cameron and Green (2) and Cameron (1) in the Laboratory of Economic Geology at the University of Wisconsin suggested that rotation properties might constitute a basis for the identification of the members of the Cobalt assemblage. The writer therefore undertook the investigation, which is one of a series of such studies now under way at this university, and this paper summarizes the results. The main purpose of the investigation has been to determine the rotation properties of the minerals, and to test the applicability of rotation properties to the problem of mineral identification. It was also desired to test the techniques and procedures outlined by Cameron and Green (2) and Cameron (1) in the determination of rotation properties.

The minerals studied were breithauptite, niccolite, safflorite, löllingite, rammelsbergite, pararammelsbergite, arsenopyrite, maucherite, gersdorffite, ullmanite, skutterudite and cobaltite. Their rotation properties as determined both in air and under oil immersion are listed in Tables I and II.

[1] Numbers in parentheses refer to Bibliography at end of paper.

TABLE I.—ROTATION PROPERTIES IN AIR.

Mineral	Crystal system	Relative dispersion of reflection rotation		Apparent angle of rotation			Dispersion of apparent angle of rotation	Amount of dispersion	Separation of isogyres	Description of figure after rotation of the analyzer	Description of figure at the 45-degree position. Analyzer and polarizer crossed
				Blue	White	Red					
Breithauptite	hex	r>v, distinct	O	5.0	4.8	1.8	r>v, distinct	2.3	60%	Gray isogyres. Fringes distinct, pink concave, blue convex.	Colors brilliant. Blue-green isogyres, yellow-green to yellow convex, violet concave.
			C	3.7	3.5	1.4					
Niccolite	hex	r>v, weak	O	2.5	3.3	3.8	v>r, strong	.9	40%	Gray isogyres. Fringes weak, pink concave, blue convex.	Gray isogyres. Fringes strong, pink concave, blue convex.
			C	1.8	2.4	2.7					
Arsenopyrite (grain)	mono	v>r, weak	O	.8	1.6	2.5	v>r, distinct	1.2	35%	Gray isogyres. Fringes weak, blue concave, pink convex.	Gray isogyres. Fringes distinct, pink concave, blue convex.
			C	.6	1.2	1.8					
Arsenopyrite section (010)	mono	v>r, weak	O	.7	1.5	2.3	v>r, distinct	1.2	35%	Gray isogyres. Fringes weak, blue concave, pink convex.	Gray isogyres. Fringes distinct, pink concave, blue convex.
			C	.5	1.1	1.7					
Arsenopyrite (section 100)	mono	v>r, weak	O	.5	.9	1.2	v>r, weak	.5	20%	Gray isogyres. Fringes weak, blue concave, pink convex.	Gray isogyres. Fringes weak, pink concave, blue convex.
			C	.4	.7	.9					
Arsenopyrite section (001)	mono	v>r, weak	O	1.0	.6	.4	r>v, weak	.5	15%	Gray isogyres. Fringes weak, blue concave, pink convex.	Gray isogyres. Fringes weak, blue concave, pink convex.
			C	.8	.5	.3					
Pararammelsbergite	orth	essentially nil	O	1.7	1.6	1.3	r>v, weak	.4	30%	Black isogyres. No color fringes.	Reddish isogyres. Weak blue concave, yellow convex.
			C	1.3	1.2	.9					
Rammelsbergite	orth	essentially nil	O	1.3	1.3	1.4	essentially nil	nil	20%	Black isogyres. No color fringes.	Black isogyres. No color fringes.
			C	.9	.9	1.0					
Safflorite	orth	v>r, weak	O	.5–1.0	.7–2.8	1.2–3.1	v>r, weak to distinct	.5 to 1.4	30%–50%	Gray isogyres. Fringes weak, blue concave, pink convex.	Gray isogyres. Fringes weak to strong, orange concave, blue convex.
			C	.4–.8	.5–2.0	.9–2.2					
Maucherite	tet	essentially nil		?	?	?	none	?	5%	Black isogyres. No color fringes.	Black isogyres separated slightly. No color fringes.
Cobaltite	iso	v>r, distinct		?	?	?	v>r, very weak	?	5%	Gray isogyres. Fringes weak, blue concave, pink convex.	Black isogyres separated slightly. Fringes very weak, pink concave, blue convex.
Ullmanite	iso	essentially nil		—	—	—	none	none	none	Black isogyres. No color fringes.	Isogyres form black cross.
Gersdorffite	iso	essentially nil or v>r, very weak		—	—	—	none	none	none	Gray isogyres. Fringes weak, blue concave, pink convex.	Isogyres form black cross.
Skutterudite	iso	v>r, weak		—	—	—	none	none	none	Gray isogyres. Fringes weak, blue concave, pink convex.	Isogyres form black cross.

TABLE II.

ROTATION PROPERTIES OF ANISOTROPIC MINERALS IN OIL. n = 1.515.

Mineral	Crystal system	Relative dispersion of reflection rotation	Apparent angle of rotation			Relative dispersion of apparent angle of rotation	Amount of dispersion	Separation of isogyres	Description of figure after rotation of the analyzer	Description of figure at the 45-degree position. Analyzer and polarizer crossed
			Blue	White	Red					
Breithauptite	hex	r>v, distinct	8.0	7.7	3.2	r>v, distinct	4.8	60%	Gray isogyres. Fringes distinct, pink concave, blue convex.	Colors brilliant. Blue-green isogyres, violet concave, yellow-green convex.
Niccolite	hex	r>v, distinct	5.1	6.4	8.0	v>r, strong	2.9	45%	Gray isogyres. Fringes distinct, pink concave, blue convex.	Gray isogyres. Fringes strong, pink concave, blue convex.
Arsenopyrite (grain)	mono	v>r, weak	1.7	3.7	4.6	v>r, dsitinct	2.9	40%	Gray isogyres. Fringes weak, blue concave, pink convex.	Gray isogyres. Fringes distinct, pink concave, blue convex.
Pararammelsbergite	orth	v>r, very weak	3.3	3.2	2.9	r>v, weak	.4	30%	Gray isogyres. Fringes very weak, blue concave, pink convex.	Reddish isogyres. Weak blue concave, yellow convex.
Rammelsbergite	orth	essentially nil	2.8	2.8	2.9	essentially nil	—	25%	Black isogyres. No color fringes.	Black isogyres. No color fringes.
Safflorite	orth	v>r, weak	1.1 to 1.7	1.9 to 5.5	2.8 to 7.5	v>r, weak to strong	1.7 to 5.8	35% to 60%	Gray isogyres. Fringes weak, blue concave, pink convex.	Gray isogyres. Fringes weak to strong, orange concave, blue convex.

PROCEDURE.

Mineragraphic Equipment.—The microscope used in this study was a standard Spencer 43 A.C. dual purpose microscope, equipped with vertical illuminating unit, polarizing plate and standard light source. A strain-free objective was found essential for accurate results; hence for all measurements of dispersion and rotation properties a special strain-free metallographic objective (6 mm., 37 ×, N.A. 0.65) was used. This objective was made by Bausch and Lomb Optical Company. The American Optical Company, however, has recently supplied strain-free, high power (40 ×) objectives that give excellent results in work on rotation properties.

A pin-hole ocular was found necessary for accurate measurements of rotation properties. Polarization figures that show weak dispersions, however, are more readily observed if this pin-hole ocular is removed, and the figure observed directly through the open microscope tube. This technique is more satisfactory for qualitative observations.

A simple mechanical stage was fixed to the stage of the microscope so that grains could be located exactly using the vernier scales. This was of great value in re-checking results at a later time, and is recommended as standard procedure in research work.

Monochromatic red and blue filters with wave lengths of 600–700 mu and 400–500 mu respectively were used for measurement of apparent angles of rotation in red and blue light. The standard 8-volt bulb of the Spencer system does not give sufficiently intense illumination for use with the blue filter. This filter decreases the amount of light entering the microscope so greatly that the resulting figure can not be used for quantitative work. A carbon arc lamp was found to give sufficiently intense illumination for use with the blue filter.

In most cases, dispersions may be observed and evaluated directly from the polarization figure given by a mineral grain when standard white light bulb illumination is used. Monochromatic filters and the carbon arc lamp are, therefore, not often necessary for purposes of identification. They are needed only when dispersions of weak or anomalous nature are encountered.[2]

For oil immersion work a special Spencer objective (1.8 mm., 95 ×, N.A. 1.25) was employed. The immersion oil used had a refractive index of 1.515. As shown by Cameron (1), oil immersion has the effect of increasing apparent angles of rotation and thereby facilitates identification. It may also increase dispersion in some minerals.

Accuracy of Measurements.—Recently it has been discovered that each microscope introduces an additional rotation of the plane of polarization of light passing upward from the surface of an anisotropic mineral. This additional rotation of the plane of polarization is due to the glass plate illuminator, and is included in each measurement of an apparent angle of rotation. Thus, the measured angle includes both the rotation due to the mineral and the rotation due to the glass plate illuminator. A correction curve may be drawn up readily for any microscope. This makes possible the correction of the measured angles

[2] Dispersions are normally described as red greater than blue or vice versa. In some polarization figures fringes of other colors may be seen. If red and blue fringes are absent, measurements in monochromatic light are the most reliable means of determining dispersions.

of rotation to the apparent angles of rotation produced by the mineral alone. In Table I, two angles are listed for each mineral. The first value represents the measured angle, and the second value is the corrected angle.

The accuracy of the apparent angles of rotation recorded in this study is ± .2 degree. Factors limiting the accuracy of the measurements are as follows:

1. Difficulty in making the extremely fine adjustment of the analyzer necessary to bring the isogyres exactly to the crossed position.
2. Difficulty in judging the crossed position of the isogyres exactly.
3. The asymmetrical nature of the polarization figures of some minerals. The causes of asymmetry have been investigated recently and will be discussed in a later paper by Cameron, Green, and the author.

Rotation Properties.—The properties determined and found to be of use in the identification of the minerals included in this study are:

1. Relative dispersion of the reflection rotation.
2. Apparent angle of rotation.
3. Relative dispersion of the apparent angle of rotation.
4. Amount of dispersion.
5. Separation of the isogyres (in percentage of field diameter). This property is of qualitative value only because it can not be directly measured. It is a function of the aperture of the lens and of the surface film.

For the general procedure used in determining these properties, and for the definition of the properties themselves, the reader should refer to the paper by Cameron and Green (2).

APPLICATION OF ROTATION PROPERTIES TO IDENTIFICATION.

On the basis of their polarization figures the minerals of this study are readily divisible into two groups.

Isotropic or Slightly Anisotropic Minerals.—The isotropic or slightly anisotropic minerals include those that are isotropic or that give apparent angles of rotation too small to measure. This group includes skutterudite, gersdorffite, ullmanite, cobaltite and maucherite. The first four of these are isometric. Maucherite is tetragonal but has a very slight degree of anisotropism, and gives apparent angles of rotation too small to measure.

Maucherite and ullmanite show no dispersion of the reflection rotation. For gersdorffite, skutterudite and cobaltite, dispersion of the reflection rotation is generally very weak, but greater for blue light than for red. It is not easy to distinguish further between the former two minerals, or among the latter three on the basis of their polarization figures. Oil immersion failed to aid in the identification of the minerals of this group. It did not perceptibly increase rotation properties or heighten dispersion as had been hoped.

Anisotropic Minerals.—The anisotropic minerals include those that are measurably anisotropic. Polarization figures offer a definite additional means of identifying the anisotropic minerals investigated. These minerals are breithauptite, niccolite, safflorite, rammelsbergite, pararammelsbergite and arsenopyrite.

Breithauptite gives a polarization figure that allows it to be distinguished at once from the other minerals of this study. It has a large apparent angle of rotation, and wide separation of the isogyres. In addition, the figure in the 45-degree position consists of striking blue-green isogyres on a yellow field, and is therefore highly distinctive. It may be noted that the original dispersion of the apparent angle of rotation given by Cameron and Green (2, Table II) for breithauptite is in error. Work in monochromatic light shows that this dispersion is greater for red light than for blue.

Niccolite is distinguished readily from breithauptite by the bright pink and blue color fringes in its polarization figure at the 45-degree position. It also differs from the other anisotropic minerals in its large apparent angle of rotation and in its dispersion of the reflection rotation which is greater for red light than for blue.

Breithauptite and niccolite are sometimes difficult to distinguish due to similarity in color, hardness, and anisotropism. This is especially true when the two are not in contact in the field of the microscope, and direct comparison is impossible. Previously, identification has been based on color differences and on microchemical tests. Polarization figures offer an effective and immediate means of distinguishing the two (whether in contact or not), because their rotation properties and polarization figures are strikingly different.

For safflorite, like nicolite, the dispersion of the apparent angle of rotation is greater for blue light than for red. Safflorite, however, is distinguished easily from niccolite by its smaller apparent angle of rotation. In addition, the figure of safflorite shows strong orange and blue color fringes at the 45-degree position whereas niccolite shows pink and blue fringes. Dispersion of the reflection rotation is opposite for safflorite and niccolite, and this contrast serves further to distinguish between them.

Table I shows that the apparent angle of rotation varies in safflorite. The recorded variation was observed in a group of nine specimens of safflorite examined. Apparently the rotation properties of safflorite, and especially the apparent angle of rotation, vary with composition in the series $CoAs_2 - FeAs_2$ (5, p 363). Further investigation of this relationship did not lie within the scope of this study, but it is felt that rotation properties may offer a method of locating a given sample of safflorite within this series. The same may be true in the case of other analogous series.

Originally it was intended to included löllingite, the orthorhombic iron diarsenide, in this investigation. A series of specimens thought to be löllingite was selected for study, including materials from the following localities:

Previous designation	Locality	Univ. of Wis. Reference No.
Löllingite	South Lorraine, Ont.	1-4-11
Löllingite	South Lorraine, Ont.	2-3-7
Löllingite	South Lorraine, Ont.	1-4-12 (1)
Löllingite	Breitenbrunn, Saxony	1-4-14 (2)
Löllingite	Zeehan, Tasmania	1-4-3
Löllingite	Cobalt, Ontario	1-4-10
Löllingite	Lölling, Huttenberg, Carinthia	7-1-10
Löllingite-safflorite	Gesellschaft Mine, Schneeberg, Saxony	1-4-15

(1) and (2) specimens supplied by Ward's Natural Science Establishment, Inc.

Similarity between the rotation properties of safflorite and the above materials led the writer to question their identity. X-ray diffraction powder photographs of the specimens were therefore taken. None of the materials gives powder patterns that agree with the powder pattern of löllingite as described by Harcourt (4, p 89). No perfect agreement with the powder pattern of safflorite was found, but all the listed materials give patterns that are much closer to the X-ray powder pattern of safflorite than to that of löllingite. Variations from the powder pattern of safflorite are attributed to compositional changes. Samples of löllingite that fit the present X-ray powder data apparently are very scarce.

Attempts were made to take single crystal oscillation photographs of some of the materials, in the hope that determinations of cell dimensions might help in identifying the specimens. The attempts were unsuccessful due to difficulty in securing single crystals.

Information concerning the rotation properties of löllingite is therefore not available at present. The samples listed above include material that forms the tiny, radially twinned, star-shaped aggregates considered characteristic of safflorite (7, p 307), (10, p 161), as well as material that forms the elongate, fibrous and radiating blades considered characteristic of löllingite (7, p 304), (11).

In arsenopyrite, as in niccolite and safflorite, the dispersion of the apparent angle of rotation is greater for blue light than for red.[8] Its polarization figure shows distinct red and blue color fringes in the 45-degree position. It may be distinguished readily from niccolite by its small apparent angle of rotation and by its different dispersion of the reflection rotation. The smaller apparent angle of rotation of arsenopyrite distinguishes it from safflorite except where the safflorite lies in the lower range of its variation in apparent angle of rotation.

One interesting feature, however, sets arsenopyrite off from all the other minerals studied. Arsenopyrite shows a reversal in dispersion of the apparent angle of rotation. In sections parallel to the *a-c* crystallographic plane, the dispersion of the apparent angle of rotation is greater for blue light than for red. Such sections show maximum anisotropism. Sections parallel to the *b-c* crystallographic plane show the same relative dispersion, but the apparent angles of rotation are smaller. In sections parallel to the *a-b* crystallographic plane, dispersion of the apparent angle of rotation is greater for red light than for blue. Thus, the reversal occurs in basal sections, which are those that show the least degree of anisotropism. To distinguish arsenopyrite from all other minerals of this study one should examine grains that show both maximum and minimum anisotropism. If reversal of the dispersion is found, arsenopyrite is indicated.

Further work is now being undertaken to explain, mathematically, the cause of reversal in dispersion. Special cases of dispersion in minerals of lower symmetry were predicted by Cameron and Green (2, p 737) but were first found in arsenopyrite. More recently they have been discovered in marcasite as well (3).

[8] In the case of arsenopyrite this is true only in sections showing a high degree of anisotropism. This is more fully explained below.

The reversal is a function of the indices of refraction and absorption of arsenopyrite for various wave lengths of light. Curves that show values of the indices of refraction and absorption plotted against varying wave length may be prepared from values given by Malmqvist (6, p 17). Ultimately it should be possible to compute from these curves the apparent angles of rotation for various sections, and thereby to obtain a mathematical explanation of the phenomenon of reversal.

Pararammelsbergite is identified at once by its distinctive and striking polarization figure. The dispersion of the apparent angle of rotation is greater for red light than for blue. In the 45-degree position the figure consists of reddish isogyres with a narrow blue fringe on one side and a broad yellow fringe on the other. No other mineral studied gives such a pattern of color fringes.

Lack of dispersion, both of the reflection rotation and of the apparent angle of rotation, is characteristic of rammelsbergite. This feature distinguishes rammelsbergite from all the minerals of the study. No color fringes were visible in the polarization figure of rammelsbergite, even in the 45-degree position. In addition, rammelsbergite has the smallest apparent angle of rotation of all the minerals studied except safflorite in the lowest range of its variation. Rammelsbergite is distinguished readily from safflorite, however, by lack of dispersion. In the past, pararammelsbergite and rammelsbergite have been extremely difficult to distinguish in polished surface, but distinction by means of polarization figures is easy and rapid.

CONCLUSIONS.

Polarization figures and rotation properties do not assist materially in the identification of the isotropic and "sensibly isotropic" minerals of this study. Dispersion of the reflection rotation occurs in certain of the isotropic minerals, but is not sufficiently distinctive to serve as a basis of identification.

Polarization figures are of great value as aids to the identification of the anisotropic minerals studied. They facilitate and corroborate mineral identification, and in some cases permit instant recognition. They are of special value in distinguishing among the troublesome orthorhombic di-arsenides, especially safflorite, pararammelsbergite and rammelsbergite. They may constitute a new method for determining the composition of members of the safflorite-löllingite series. Polarization figures and rotation properties are a valuable new aid to the identification of the anisotropic nickel, cobalt and iron sulfarsenides in polished surfaces.

The use of oil immersion does not greatly facilitate identification of the minerals studied. Oil immersion failed to modify rotation properties of the isotropic and weakly anisotropic minerals enough to permit identification. Most of the anisotropic minerals can be identified from their polarization figures observed in air; hence oil immersion is unnecessary. In cases where two minerals are nearly the same in rotation properties in air, oil immersion is of greater value. Table II shows that oil immersion increases the spread of the apparent angles of rotation for the various specimens of safflorite. The spread of these angles in oil is almost double their spread in air. This will be of use in studying the relationship between apparent angle of rotation and composition in the safflorite-

löllingite series. Oil immersion will thus be of great use in the determination of the composition of safflorite-löllingite once this relationship is established.

Identification work using polarization figures and rotation properties is readily carried out using standard mineragraphic equipment.

ACKNOWLEDGMENTS.

Grateful acknowledgments are due to Dr. E. N. Cameron, who suggested this study, and to Mr. L. H. Green for their assistance and advice during the investigation, and for their constructive criticism of this paper. Thanks are due to Mr. George Sanderson, Mr. G. J. Anderson and Mr. R. B. Ford for their aid in preparing oriented sections of arsenopyrite. Thanks also are due to Dr. G. G. Suffel of the Geology Department, University of Western Ontario, London, Ontario, who supplied crystals of arsenopyrite. Mr. S. W. Bailey has given invaluable assistance in the X-ray investigations of löllingite-safflorite. The Wisconsin Alumni Research Foundation, University of Wisconsin, Madison, Wisconsin, supplied funds for the investigation.

UNIVERSITY OF WISCONSIN,
MADISON, WISCONSIN,
April 1, 1953.

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DISCUSSION

BANDED HEMATITE JASPERS OF SOUTH SINGHBHUM.

Sir: We wish to express our thanks to Dr. Bond for his comments and congratulations, published in your December issue.

Dr. Dunn, in the January issue, introduces some rather irrelevant matter. We note that his letter has the general title Banded hematite quartzites, but we wrote upon the banded hematite jaspers of the iron ore field of Singhbhum and the adjoining States of Orissa.

Dunn considers our following statement ambiguous: "after we had pointed out the incorrect placing of the 'basal' conglomerate in the Geological Survey publications (which was originally based on correlations farther afield), Dunn entirely revised the succession in this area."

There is no ambiguity. As is mentioned in Dunn's letter we first pointed out the error in 1931. We did not re-map the area, but we did collect, somewhat casually, in the course of our other duties, further information for publication, and we informed the Survey of this in 1938. The onus of re-mapping the area was on the Geological Survey, and Dunn's reference to "the long years between 1922 and 1938" leaves our withers unwrung.

We have a holograph letter written to one of us by Dunn, when he went to map the area in December, 1938, in which, after commenting on the work of his predecessors, he writes: "your view of the congl. I certainly confirm."

The matter is of general interest only because of Dunn's remark that "the immediate neighbourhood of the larger iron ore deposits in Singhbhum provides little evidence to support any theory of their origin." We found what we consider to be important evidence in these very rocks in the iron ore field, and we pointed out the possibility that banded rocks elsewhere might not be similar, and might be of doubtful correlation.

The great bulk of the banded hematite-silica rocks in Singhbhum and Orissa occurs in the iron ore field we were discussing, and here, in general, the silica is jasper, and is not re-crystallized. Dunn's work was mainly elsewhere, except for the northern fringe that he mapped, as mentioned, in 1938. His remarks on re-crystallization to quite coarse quartzite rocks must, we presume, refer to occurrences in these other areas. We are not familiar with these areas, and we did not discuss them; but we did refer to his silicification theory, since he extended it to the iron ore field in which we were working, and from which our specimens were derived.

We note he now states that he "must accept the observed evidence of the replacement origin of these rocks in many parts of Singhbhum and adjacent areas. . . ." He does not specify that this includes the iron ore field, but it would seem that he intends this. He does not, of course, give details of the

observed evidence within the limits of his letter, but he gave this evidence in 1941 in his paper on The origin of banded hematite ores in India, published in ECONOMIC GEOLOGY, Vol. 36, pp. 355–370, and at that time he seemed to be less certain, as he wrote (p. 366):

"It must be confessed that, although evidence of the secondary origin of the silica is so widespread, there is no evidence in South Singhbhum and Keonjhar denying the sedimentary origin of the silica, either as a chemical precipitate or organically deposited."

And again (p. 370):

"The writer does not deny the probability of the sedimentary origin of the cherty silica, but points out that there is no direct evidence in support, whereas examples of silicification of the associated banded sediments are numerous."

Dunn mentions, as an example of the preservation of delicate textures through severe stages of metamorphism, the amygdules in the re-crystallized lavas of Singhbhum. He could scarcely have chosen a more unfortunate example. Most of the amygdules have been so reconstituted internally that their original structure cannot be guessed.

As to his other comments, we leave it to your readers to draw their own conclusions from the evidence we have presented.

Regarding Professor Moore's letter in the June–July issue, we regret we were not previously aware of his paper, but it is interesting that Dr. Bond and we should have independently come to the same conclusion as Professor Moore on the explanation of the difference between the elaborately crumpled, and the shattered types of banded iron formation.

E. SPENCER,
F. G. PERCIVAL.

HASLEMERE, SURREY, ENGLAND,
May 4, 1953.

REVIEWS

Man and His Physical Universe. By RICHARD WISTAR. Pp. 488; figs. 303. John Wiley & Sons, New York, 1953. Price, $4.75.

This book is intended as a text for a course in physical science. It approaches the subject in a new manner. Instead of a digested or condensed version of astronomy, geology, physics and chemistry, this book integrates all of the subject into subject matters. It is planned for a year's course that brings in the important features of each of the four main physical sciences. The novel manner is to introduce the student to the subject of light by the consideration of a camera. From that one is led into the various physical features of light. Similarly, sound is taken up through a consideration first of an automobile horn. The physics of the eye introduces the subject of waves. The first unit is largely devoted to physics, with chemistry interrelated. The second unit deals with the solar system, and gives an idea of the method of studying astronomy, of the earth, of the planets, and of the solar system, and a history of the development of ideas about the structure of the universe.

The third unit is the story of the earth in which the author takes up changes in the earth's surface, the interior of the earth, the effect of winds, temperature, changes in landscape, and "Up from the Sea" (historical geology). It then concludes with the development of early mammal up to man. The fourth unit is "forecasting the weather." It brings in not only meteorology but a considerable amount of physics. The first unit deals with electricity and magnetism, bringing in communications. The sixth unit is called "atomic structure" in which one is introduced to the inside of the atom and the part it plays in modern physics, chemistry, and atomic energy.

The book as a whole is extremely well unified and each of the subjects is interrelated with the other rather than treating them separately. Theoretical aspects are brought in in their proper place. For colleges that give a general science source this book should serve a very excellent purpose.

Petroleum in the Western Hemisphere. Pp. 183; tbls. 17; figs. 20. Report of the Western Hemisphere Oil Study Committee of the Independent Petroleum Association of America, Washington, 1953.

This study is the result of the work of 40 members of the Committee, with Charlton H. Lyons as Chairman, and covers petroleum economics, production, law, geology and engineering. It is stated in the foreword, "The findings of this study demonstrate that neither the United States nor the Western Hemisphere need ever be short of petroleum products in the foreseeable future. Certain threats, however, are revealed. The study points up these threats and provides a guide to a proper and sound course of action."

The content is made up of reports of five subcommittees, namely, Western Hemisphere Oil Study; Production, Productive Capacity and Reserves; Supply and Demand; Materials; and Government Policies and Laws in (1) producing, and (2) nonproducing countries.

The subcommittee report on Production, Productive Capacity and Reserves is of greater interest to the geologist. This part deals with (I, II) the Production History, Known Reserves, and Potential Reserves of the presently producing countries of the Western Hemisphere; (III) Productive Capacity or Availability, both present and future of the different countries; (IV) Drilling Activity; and (V) Summary. The chairman of this subcommittee was A. I. Levorsen, and under his leadership a thorough job was done. Their summary of the known reserves of the Western Hemisphere is 46 billion barrels out of a world total of 106, divided as follows: United States, 69.7 percent; Venezuela, 21.7; Canada, 3.0; Mexico, 3.0; and all others 2.6 percent. They point out that the prospective area within the United States in which oil and gas may be found is about 100 times as large as all areas so far discovered.

One may detect a little bias in the book, but it does assemble much valuable data.

Geology and Mineral Deposits of Pre-Cambrian Rocks of the Van Horn Area, Texas. By PHILLIP B. KING AND PETER T. FLAWN. Pp. 218; pls. 36; figs. 24; tbls. 30. University of Texas Publication 5301, Austin, 1953.

This comprehensive paper has been prepared in cooperation between the Bureau of Economic Geology of the University of Texas and the U. S. Geological Survey. Dr. King, of the Survey, and Dr. Flawn, of the Bureau, have carried on the field work and collaborated in the joint report. Each author has written special sections such as Van Horn Mountains (Mica Mine area), Wylie Mountains, Eagle Mountains, Carrizo Mountains by Flawn, and Sierra Diablo foothills, Pump Station Hills, structural and stratigraphic problems of Precambrian rocks by King, and both authors have contributed to the section of economic geology, as well as to the introductory part. An appendix includes a road log along U. S. Highway No. 80 through the Carrizo Mountains, and also a report on a gravity survey at the Hazel Mine written by V. E. Barnes and Flawn. The maps of Precambrian rocks of the Carrizo Mountains and Sierra Diablo foothills are engraved in color. Many chemical analyses and estimated modes of Precambrian rocks are included in the tabular materials.

In addition to the Precambrian rocks in each of the seven areas treated, the authors describe the Permian, Cretaceous and Tertiary works and the structure. Under "General Problems of Precambrian Rocks," King deals with the structural history, pattern, and regional relations, and Flawn of the problems and interpretation of the metamorphism.

The economic geology includes the copper-silver fissure veins of the Hazel and other mines, mica feldspar, talc, nitrate and turquoise.

The report is a notable contribution to the geology of Texas.

The Geology of Ireland. By J. K. CHARLESWORTH. Pp. 276; pls. 21; figs. 99. Oliver and Boyd, Ltd., Edinburgh, 1953. Price, 25/– net.

This book by text, photos and drawings gives a readable picture of the geology of Ireland.

The arrangement is historical, from Precambrian to Recent, including the periods of orogeny. The stratigraphy, fauna, structure, igneous rocks, geomorphology and mineral resources of each period are given in considerable detail and the late Glacial and Post-Glacial events are shown by an interesting chart.

The book contains a lot of detailed local descriptions that make a bit tiresome reading for those not specifically interested in the local geology, but here and there

are features of larger interest that bear on broader problems of the relation of the geology of Ireland to that of Great Britain and western Europe.

Treatise on Ores and Assaying. By LAZARUS ERCKER. Translated by ANNELIESE G. SISCO and CYRIL STANLEY SMITH. Pp. 360; illust. University of Chicago Press, 1953. Price, $10.00.

We welcome another of these interesting translations of 16th century books. This one is by the same authors who translated the delightful little book called "Bergwerk und Probierbüchlein." This book by Lazarus Ercker was written in 1574 when Shakespeare was only two years old. After an interesting dedication, preface and introduction, there follow five separate books. The introduction deals with assaying and what an assayor should know.

The first book deals with silver ores and the author starts off by explaining why he deals with silver first instead of gold. He points out that other assays and the preparation of equipment have their origin in the techniques of silver assaying and "flow therefrom as from a spring." Following the silver ores the next two books relate to gold and copper, the fourth book is on lead, tin and other metals, and the fifth book is on saltpeter. A conclusion and a table of contents follow. In the appendix there is a list of the previous editions showing their interesting title pages and an account of the life of Sir John Pettus, a system of weights and measures used by Ercker, and then a list of works cited by the translators.

The book is written in the quaint style of the 16th century and of course contains many of the interesting wood cuts, first made so generally familiar to English reading audiences by "De Re Metallica." Ercker was a noted authority of his time and his book became the standard book for the use of all related to assaying, metallurgy, and in many parts to information on minerals. It is surprising how much was known about assaying and refining in Ercker's time.

This book will be wanted in the library of every metallurgist and also will be of interest to the mining engineer and the chemist. The translators appear to have done a very excellent job and the book is nicely printed and the illustrations well reproduced.

The Liassic Ironstones. By T. H. WHITEHEAD, W. ANDERSON, VERNON WILSON and D. A. WRAY. Pp. 211; figs. 24; pls. 8. Memoirs of the Geological Survey of Great Britain, London, 1952. Price, £1, 5s.

This book brings together in one volume most of what has previously been known about the chief iron-ore fields of England, together with much new information relating to the petrography, the paleontology, and X-ray examination of the oolites.

Chapter I is a general introduction dealing with the stratigraphic distribution, structures and methods of working. Chapter II is petrography, and deals in detail with various types of ironstones and the minerals found in them. Chapter III takes up the iron ores of the Cleveland district; Chapter IV, that of the Frodingham district of Lincolnshire; Chapter V, the ironstone of Lincolnshire, Leicestershire and Rutland; Chapter VI, the ironstones of north Oxfordshire, southwest Northamptonshire, and southeast Warwickshire.

Under each of these four main districts is given full detail of the geology, the structure, the stratigraphy, details of the seams themselves, the paleontology, and references. Many illustrations complete each of the chapters.

The book as a whole furnishes the fine compilation of data relating to sedimentary iron ores typical of those found in other parts of the world.

The Science of Petroleum, Volume VI, Part I. The World's Oilfields. The Eastern Hemisphere. Edited by V. C. ILLING. Pp. 174; figs. 60. Oxford University Press, London, 1953. Price, $20.00.

It is appropriate and timely that The Science of Petroleum, by far the most ambitious and comprehensive reference work on the petroleum industry in print, should now be brought up to date. During the fourteen years that have elapsed since the original four volumes were published (1938), "the annual output of petroleum has continued to expand * * * areas which were of relatively small importance in 1938 have come to the fore. Technical advances in all branches of the petroleum industry have been remarkable, and many problems of exploration and development which could not be dealt with when the first volumes were produced are now capable of ready solution."

Volume VI, Part I, represents the first section of a revision and amplification of Volume I. It deals solely with the occurrence and exploitation of petroleum in the Eastern Hemisphere, supplementing a single section (Section 4) of Part I of the original Volume I. It is fortunate that, for the preparation and editing of this new material, it has been possible to enlist as editor, Professor V. C. Illing, who was himself honorary associate editor of, and a voluminous contributor to Volume I. It is also fortunate that several of the authors of key chapters in the original volume should have been persuaded to deal with the same areas in the new volume. These authors are likely to realize—and hence to portray—most vividly the changes that have come about in the interim.

How profound are the changes that have occurred in the last decade, or so, in our knowledge of the occurrence and distribution of petroleum, and how pressing, in consequence, is the need for supplementing Volume I, may be inferred from a few simple comparisons.

In 1938, Eastern Venezuela boasted but a single modest oil field, against more than a score of larger fields today. In Volume I, the oilfields of West Texas and Southeastern New Mexico, where limestone reefs constitute the reservoir rocks in many of the great oilfields so far developed, could be described and discussed in some detail by one of the best informed and most competent of American geologists, with no single mention of the word reef. The "future production" of the state of Illinois, which had already produced something over 400 million barrels of oil, and has since produced double that amount, could plausibly be estimated at "nearly 50 million barrels." The oilfields of the region we commonly designate as the Middle East could be amply covered without any reference to Saudi Arabia, Kuwait, Qatar or Bahrein, countries which currently produce a total of well over 1 million barrels daily.

The Middle East, as would have been anticipated, having in mind the tremendous development in its producing capacity since Volume I was published, is the subject of the outstanding chapters in the new volume. From a space of 10 pages in the original volume, the discussion of the Middle East has expanded to 34 pages in the supplementary text. The photographs which illustrate the chapter on Persia, by George M. Lees, are magnificent portrayals of geologic structure.

The discussion by this author emphasizes a factor in oilfield genesis which deserves more attention than it has generally been accorded by most American petroleum geologists. This factor is "caprock efficiency." Accumulations of petroleum may be confidently expected in the Middle East in any one of a number of porous reservoir rocks of quite different ages. The indispensable common attribute is that there be present, overlying the reservoir, an adequate "barrier to upward movement and escape of oil." A barrier of this type, commonly serving as

caprock in the highly folded fields already discovered, is the "thick Lower Fars series (of Miocene age) with its impervious and plastic beds of salt, salty marl and anhydrite." This series forms the caprock uniformly over the 60-mile long Kirkuk Oilfields, for example, despite the fact that the limestone reservoir itself, though continuous, is of Lower Miocene and Oligocene age at one end of the field and of Upper and Middle Eocene age at the other.

The organization of the material in the new volume is admirable. The Eastern Hemisphere is divided into four sections each of which is first treated as a unit for discussion, then broken down into constituent countries, or geographical components for individual attention. The four sections are: Europe; The Middle East; The Far East and Australia; and Africa. Particularly useful is the general treatment of each of the major subdivisions of the oil-producing regions of the earth, which preceded the detailed comment on individual countries.

While the general title is The World's Oilfields, it is gratifying to discover that the text has been extended to cover non-producing areas, such as Australia, as well. Notable omissions from the list of Western European countries discussed individually (which includes Switzerland) are Spain and Denmark. The Iron Curtain countries, Austria and Hungary, are included. Readers who hope to find descriptions of the oilfields of the U.S.S.R., however, will be disappointed. All "efforts to obtain contributions on the U.S.S.R. from Russian authors were unsuccessful." Altogether, some 30 different authors from the Western World have written part or all of one or more chapters.

The illustrations for The World's Oilfields are well selected and generally adequate. It seems unfortunate that no map accompanies the discussion of the continent of Australia, although the reader can refer back to Volume I which does contain a map of Australia. A praiseworthy feature of the illustrations, which for the most part are simple line drawings, is that they have been reduced to uniform draftsmanship and—with a few exceptions—to a single page, or less, in size, still with perfect legibility.

Neither the original Volume I nor the new Volume VI, Part I, discusses the petroleum prospects of the Philippines, Formosa or New Zealand. New Zealand is generally placed in the Eastern Hemisphere and its petroleum possibilities are surely as impressive as those of Tasmania, which is discussed. These are small omissions, more than compensated by the excellence of other sections of this outstanding treatise on the world-wide search for and production of petroleum. The readers of The World's Oilfields, The Eastern Hemisphere, will look forward with zest to the early appearance of a companion volume—The Western Hemisphere—which should prove to be even more significant.

WALLACE E. PRATT.

CARLSBAD, NEW MEXICO,
June 8, 1953.

BOOKS RECEIVED.

FRANK G. LESURE.

U. S. Atomic Energy Commission—Oak Ridge, Tennessee, 1952–53.

RMO-44. Experimental Simulation of Plateau Type Uranium Deposits. GEORGE W. BAIN. Pp. 210; pl. 1; figs. 56; tbls. 17. *Includes summary of geologic occurrence, and results of experimental investigation. Deposition of uranium occurred during artesian circulation.*

Geol. Rept. G-123. Field Tests for the United States Atomic Energy Commission on the Use of the Seismic Geophysical Method for Tracing "Buried Channels" in the Monument Valley Area, Arizona. DART WANTLAND and ROBERT D. CASEY. Pp. 68; figs. 29. (Prepared by the U. S. Bureau of Reclamation for AEC.)

Thermodynamic Properties of Sodium-Aluminum and Potassium-Aluminum Silicates. K. K. KELLEY, S. S. TODD, R. L. ORR, E. G. KING, and K. R. BONNICKSON. Pp. 21; figs. 4; tbls. 37. U. S. Bureau of Mines, Rept. of Inv. 4955, Washington, 1953.

Division of Geology and Geography, Annual Report for 1951–52. Pp. 118. National Research Council, Washington, 1953.

Manual for Geometrical Crystallography. CALEB WROE WOLFE. Pp. 263; figs. 187. Geopublishing Co., Watertown, Mass., 1953. *Detailed account of crystal lattices, symmetry, crystal systems and classes, crystal projection and measurement, and crystallographic calculations. Contains several misstatements of fact and very numerous errors.*

Minerals Yearbook, 1950. Pp. 1690. U. S. Bureau of Mines, Washington, 1953. Price, $4.50.

Outlines of Structural Geology. E. SHERBON HILLS. Pp. 182; pls. 4; figs. 107. John Wiley & Sons, Inc., New York, 1953. Price, $3.00. *3rd Edition Revised. A brief, well illustrated summary of principles of structural geology.*

California Journal of Mines and Geology. Vol. 49, Nos. 1 and 2. Pp. 192; pls. 3; figs. 48. Contains 2 papers: Annual Rept. of the State Mineralogist, Chief of the Division of Mines for the 103d Fiscal Year, July 1, 1951 to June 30, 1952, by Olaf P. Jenkins, and Mines and Mineral Deposits of San Bernardino County, *California, by Lauren A. Wright, Richard M. Stewart, Thomas E. Gay, Jr. and George C. Hazenbush. Description of metallic and nonmetallic deposits including limestone, saline minerals and tungsten.*

Quarterly of the Colorado School of Mines—Golden, 1953.

Vol. 48, No. 1. Graphite Formation in Ductile Cast Irons. V. A. ALTEKAR and LUIZ ANTONIO DE ARAUJO. Pp. 67; figs. 32; tbls. 10. Price, $1.00.

Vol. 48, No. 2. A Study of Asphalts and Asphaltic Materials. GEORGE W. LEMAIRE. Pp. 89; figs. 23; tbls. 20. Price, $1.50.

Illinois State Geological Survey—Urbana, 1953.

Rept. of Inv. 163. Viscosity Studies of System CaO-MgO-Al_2O_3-SiO_2: III, 35%, 45%, and 50% SiO_2. J. S. MACHIN, TIN BOO YEE, and D. L. HANNA. Pp. 9; figs. 3; tbls. 3.

Rept. of Inv. 164. Water Soluble Salts in Limestones and Dolomites. J. E. LAMAR and RAYMOND S. SHRODE. Pp. 97–112; fig. 1; tbls. 7.

Circ. 183. Short Papers on Geologic Subjects. Some New Observations on Niagran Reefs in Illinois. HEINZ A. LOWENSTAM. **The Chouteau Formation of Illinois.** THOMAS C. BUSCHBACH. Pp. 100–115; figs. 10.

Circ. 184. Sands and Silts of Extreme Southern Illinois. RAYMOND SHRODE and J. E. LAMAR. Pp. 28; fig. 1; tbls. 5.

Indiana Geological Survey—Bloomington, 1953.

Field Conf. Guidebook 6. Ordovician Stratigraphy, and the Physiography or Part of Southeastern Indiana. JOHN B. PATTON, THOMAS G. PERRY, and WILLIAM J. WAYNE. Pp. 29; pls. 4. Price, 50 cents.

Progress Rept. 5. Preliminary Report on High-Silica Sand in Indiana. HAYDN H. MURRAY and JOHN B. PATTON. Pp. 35; pl. 1; figs. 3. Price, 50 cents.

The Kansas Scene. GRACE MUILENBURG. Pp. 48; figs. 81. Kansas Geological Survey, Lawrence, 1953.

Surface Waters of Missouri. HARRY C. BOLON. Pp. 934; pls. 6. Missouri Geological Survey, Rolla, 1952.

North Dakota Geological Survey—Grand Forks, 1953.

Rept. of Inv. 10. Geomagnetic Survey of Part of the East Edge of Williston. Basin. HARALD C. HARALDSON. *1 sheet includes map: scale 1 inch equals 2 miles and text.*

Circ. 14. Summary of the Wanete Oil Company, M. O. Lee and Silas Engen No. 1. SIDNEY B. ANDERSON. Pp. 17.

Circ. 15. Summary of the Alvin Peplinski No. 1 Well. SIDNEY B. ANDERSON. Pp. 7.

Oregon Department of Geology and Mineral Industries—Portland, 1953.

Bull. 37. Geology of the Albany Quadrangle, Oregon. IRA S. ALLISON. Pp. 18; pls. 2. Price, 75 cents.

Bull. 44. Bibliography of the Geology and Mineral Resources of Oregon. January 1, 1946 to December 31, 1950. Pp. 61. Price, $1.00.

Geology and Mineral Deposits of Pre-Cambrian Rocks of the Van Horn Area, Texas. PHILLIP B. KING and PETER T. FLAWN. Pp. 218; pls. 36; figs. 24; tbls. 30. University of Texas Pub. 5301, Austin, 1953. *A detailed account of the stratigraphy, structure and petrology of the area. Economic deposits include some copper and silver.*

Oil Well Cements. W. C. HANSEN. Pp. 32; figs. 4. U. S. Steel Corp. Tech. Paper 158, New York, 1953.

World Resource Statistics, A Geographic Sourcebook. JOHN C. WEAVER and FRED E. LUKERMANN. Pp. 166. Burgess Publishing Co., Minneapolis, 1953. *Contains statistical information on populations, power, metallic and nonmetallic minerals, forests, fisheries, agriculture and industry.*

Geology of the McKnight Lake Area. H. E. HUNTER. Pp. 6; pl. 1. Manitoba Dept. of Mines, Winnipeg, 1953.

Quebec Department of Mines—Quebec, 1953.

Geol. Rept. 50. Kensington Area. E. AUBERT DE LA RUE. Pp. 35; pls. 9.

Geol. Rept. 54. Temiscamie River Area. WILLIAM G. WAHL. Pp. 32; pls. 5.

Map. No. 1952–53. Southern Part of James Bay Lowland. Scale: 1 inch to 8 miles.

The Australian Mineral Industry, Vol. 5, No. 3. Pp. 59–91. Bureau of Min. Res., Geol. and Geophys., Melbourne, 1953.

Bibliographie Géologique du Congo Belge et du Ruanda-Urundi. Vol. III, 1935–44. Pp. 131. Musée Royal de Congo Belge, Tervuren, 1952.

Wells and Boreholes for Water Supply. J. E. DUMBLETON. Pp. 137; figs. 39. The Technical Press, Ltd., London, 1953. Price, 17/6d. *Brief discussion of springs and yields of wells, followed by details of boring of wells, properties of water and water analysis and purification, mostly applied to Great Britain.*

Carte Géologique de l'Afrique Equatoriale Française et du Cameron. MAURICE NICKLÈS. Pp. 109. Gouvernement Général de l'Afrique Equatoriale Française, Direction des Mines, Paris, 1952. *Description of the regional stratigraphy of French Equatorial Africa and Cameroun. Geologic map, scale: 1 to 2,000,000 in 3 sheets.*

Acta Geologica. Tom. II, Fasc. 1–2. Pp. 190. Magyar Tudományos Akadémia, Budapest, 1953. *14 papers of general interest.*

Sveriges Geologiska Undersokning—Stockholm, 1948–52.

Asbok 41, N:o 9. The Adak Area, A Review of Geology and Ore Deposits. S. GAVELIN. Pp. 54; pls. 2; figs. 19; tbls. 3. Price, 2 kronor.

Arsbok 45, N:o 2. Lime Metasomatism and Metamorphic Differentiation in the Adak Area. SVEN GAVELIN. Pp. 52; figs. 18; tbls. 6. Price, 3.50 kronor. *Descriptions of mineralization processes in silicate rocks leading to formation of lime-silicates.*

Académie Serbe des Science—Belgrade, 1952.

Recueil des Traveaux, T. XXII, No. 3. Pp. 176. *Contains twelve papers of general interest on mineralogy, structural geology, stratigraphy and paleontology.*

Recueil des Travaux, T. XXIII, No. 4. Pp. 275. *15 papers including some on mineralogy, stratigraphy and structural geology. Papers of economic interest includes discussions of cement rock, and nickel and chromium mineralization.*

Monographs Vol. CXCVII, No. 4. Geology and Tectonics of the Area of Ulcinj. M. T. LUKOVIC and K. V. PETKOVIC. Pp. 62; pl. 1; figs. 16. *Stratigraphy and tectonics of the area. Mineral deposits include bauxite.*

SCIENTIFIC NOTES AND NEWS

DAVID A. ANDREWS, representing the U. S. Geological Survey and TCA, K. P. WANG, representing the U. S. Bureau of Mines, and EARL M. IRVING, representing the U. S. Geological Survey and MSA, were the technical American delegates to the ECAFE *ad hoc* committee conference on the development of mineral resources in the Southeast Asian area, which meeting was held in Tokyo, April 20–May 1. Following the meeting, the conference members were conducted on a 10-day tour of metal mines, smelters, refineries, and coal fields of southern Japan. Twelve Southeast Asian countries, including Russia, were represented. Among many other personalities attending the conference were Dr. N. H. FISHER, Chief Geologist, Bureau of Mineral Resources, Australia; V. R. KHEDKER, Director of Indian Bureau of Mines; Dr. H. M. E. SCHIRMAN of the Netherlands; Mr. VIJA SETHAPUT, Chief Geologist of the Royal Department of Mines; Mr. SURODJO, Director of the Indonesian Geological Survey; Prof. NICOLAY P. SEMENKO and Prof. MICHAEL I. VARENTSOV, Academy of Sciences of Russia; Dr. F. DIXEY, Director of British Colonial Geological Surveys; Drs. SEITARO TSUBOI, TAKEO WATANABE, TAKEO SAKAMOTO, and TOMOFUSA MITSUCHI and others representing Japan; and HAROLD SERVICE, Director of the Malayan Geological Survey. Mr. F. BLONDEL of France, Mr. GEORGE SHAW of Canada, Mr. HANS R. REINBACH, Mr. RENÉ G. LEHMAN of France, and Mr. N. E. S. RAGHAVACHARI of India, were invited as Technical Consultants to the Conference. The first part of the conference took up technical problems of mineral resources development and supply in Southeast Asia, especially with reference to coal, iron and steel, ferro-alloys, the light metals and fertilizer minerals. The second part of the conference was concerned with the status of geological surveys in the region, and how to promote increased activity in the important field. The conference was considered a great success and was made most enjoyable by the host government, Japan, being the first UN conference to be held in Japan.

A. H. HUBBELL has been appointed senior associate editor of the Engineering and Mining Journal, and A. W. KNOERR will become managing editor. Mr. Hubbell, a graduate of the School of Mines of Columbia University in New York City, joined the staff of E&MJ in 1917, and has held the post of managing editor since 1922. He moves to the position of senior associate editor in order to devote his full time to coverage of the iron ore mining industry and of mining practice in general. Mr. Knoerr joined the staff of E&MJ in 1944. He is a graduate of the Wisconsin Institute of Technology and of the Missouri School of Mines. Prior to joining E&MJ, he served as a mining engineer on the staffs of Sunshine Mining Co., Kellog, Idaho; Idaho Mining Co., Ouray, Colo., and other western mining operations.

L. F. PADDISON, mining and geological engineer with the United States Smelting, Refining, and Mining Co., at Boston, Mass., has retired. With the company since 1914, less two years with Magma Copper Co., Mr. Paddison has been active in exploration and operating work in the United States, Canada, and Mexico and will continue to engage in a limited amount of consulting work.

F. M. VAN TUYL, head of the geology department of the Colorado School of Mines in Golden since 1919, will return this summer with the rank of professor emeritus. L. W. LEROY, professor of geology at Mines since 1942, will succeed Dr. Van Tuyl.

R. W. STONE is serving as Acting Director of the Topographic and Geologic Survey of Pennsylvania, as a temporary position until a successor to Mr. S. H. CATHCART is selected and appointed.

EDWARD STEIDLE, retiring Dean of the School of Mineral Industries, Pennsylvania State College, is leaving for the Belgian Congo.

ELWOOD S. MOORE has been appointed as Associate with Behre Dolbear and Company.

L. S. WELDON has been appointed Executive Vice-President of Hollinger Consolidated Gold Mines, Ltd. He had been Executive Engineer since 1950.

A. C. CARON, JR., formerly with the Glenconna Mining Co., Nirrie Lake, Chibougamau, Que., has been appointed Chief Engineer for the Cassair Asbestos Corp., Ltd., Cassair, B. C.

J. C. DAVEY has been appointed Senior Mining Engineer for the Colonial Development Corp., Ltd., at their head office in London, England. He was formerly General Manager for the Egyptian Phosphate Co., Ltd., Sefaga, Upper Egypt.

NOEL W. HENDRY, Chief Geologist for the Canadian Johns-Manville Company, Ltd., Asbestos, Que., has been promoted to the position of Exploration Manager.

TOM H. W. LOOMIS, JR., has been appointed Geologist for the United States Atomic Energy Commission, for whom he is now carrying on reconnaissance work in the western States, with headquarters in Denver, Colo.

D. L. MACQUARRIE, JR., is now employed as Geologist for the Shell Oil Company, Ltd., with headquarters at Edmonton.

R. P. JORDAN, JR., has been appointed Field Geologist for Noranda Explorations, Ltd., with headquarters at Parksville, B. C.

MERVYN L. WADE, former Geologist with the Adelaide Department of Mines, is now Chief Geologist with Mount Lyell Mining and Railway Company, Ltd., Queenstown, Tasmania, Australia.

ERNEST N. PATTY and MERLE A. TUVE were given honorary degrees at The University of Alaska commencement on May 11th.

H. KIRK STEPHENSON, from Los Alamos Scientific Laboratory, has been appointed program director for earth sciences in the National Science Foundation.

MARLAND P. BILLINGS, Professor of Geology, Harvard University, on May 14th at the University of Minnesota delivered the annual William Harvey Emmons lecture; his subject was "Metamorphic Zones or Facies in Central New England." On May 15 Dr. Billings led a seminar discussion of the origin, zonal and facies classification or metamorphic rocks. On May 16 and 17 a field conference was held on the Precambrian rocks near Duluth. The first day was devoted to a study of the Duluth gabbro and its contact effects on intruded rocks, the various kinds of intrusive rocks in the Duluth mass. The second day was devoted to an examination of the progressive regional metamorphism in the Precambrian Thomson slate belt from the slates of Jay Cooke State Park westward through the phyllite and schist facies to gneissic rock near Denham, Minnesota. The first conference was led by Dr. G. M. SCHWARTZ and Dr. SAMUEL S. GOLDICH.